Geomatics in Ecosystem Assessment and Management

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Abstract The development of Geomatics in recent years has been revolutionized by rapid advances in computer hardware and software. Geomatics has been successfully applied in biodiversity assessment, wetland mapping, drylands degradation assessment, measurements of land surface and marine attribute, and many other applications. Geomatics technologies benefit the ecosystem assessment and management process at all stages, including data collection, data management, data analysis and modeling, and presentation of results. The chapter conducts a review of the Geomatics technologies and their application in a practical framework for ecosystem assessment and management.

Keywords Geomatics · Ecosystem assessment and management · GIS · Multi-criteria evaluation

1 Introduction

With the transition of the ecosystem studies from ecosystem structure, condition, and function assessment to ecological procedure assessment, the facing problems are becoming more complicated and synthesized: The research scale is long termed and globalized; the research method is quantified; the research objective is management oriented. Obviously, the traditional statistical method are not capable to finish the job any more, a new technology—Geomatics technology [including

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tools and techniques used in Remote Sensing, Geographical Information System (GIS), and Global Positioning System]—has become the most efficient and convenient method to do research. Geomatics is "a powerful set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world for a particular set of purposes [1]." It has been widely used to support the process of environmental assessment and management.

The term "remote sensing" is broadly defined as the technique(s) for collecting data about an object from a distance from the object and the recorded data are usually saved as images. Based on the information being collected and the technology used to collect data, remote sensing products can refer to satellite imagery, aerial photographs, or radar data from active or passive microwaves [2]. Remote sensing technology has been increasingly used in the past several decades to conduct research from local to global scales. The evolvement of technology has enabled the data collection from pure visual imagery (e.g., aerial photographs) to multi-spectral imagery (e.g., Landsat products). The spatial and temporal resolution has improved over time and reached a level at which high-quality spaceborne imagery of any location on earth can be acquired in a timely manner.

Geographical information systems are widely used as tools to collect, store, manage, analyze, and display geographical data. GIS can be used to build the inventory of any type of data with spatial attributes, which have seen an expanding usage in both human topics (e.g., demographic databases) and natural studies (e.g., distribution of environmental elements and factors). GIS also provides a growing and large number of tools that can be used to analyze and assess the characteristics of data over data space, temporal space, and spatial space. More importantly, GIS offers a practical environment to manage multiple types of database, which ensures a platform for a sustainable management system. GIS can also provide inputs to both static and dynamic ecosystem models [3]. For example, a static model may be used to estimate soil erosion based on soil type, meteorological data, and terrain characteristics, whereas a dynamic GIS model could be used to represent a spatial landscape transition pattern at different time periods. Another impressive characteristic of GIS is that it can visualize and present of simulation results in maps, even in three-dimensional view.

The role of Geomatics in ecosystem studies is expanding as researchers exploit the increasingly sophisticated capabilities of technologies in GIS and remote sensing. Recent advances include the ability to store and manage Big Data (large datasets) and to perform more spatial and statistical analyses. In particular, GIS has relevance to the system modeling process that is such an essential component of the usual assessment and management procedure. Therefore, Geomatics will continue to be applied as an essential toolset for data acquisition, analysis, and management in the fields of environmental assessment, planning, and management.

2 Application of Geomatics in Ecosystem Assessment and Management

Geomatics technologies benefit the ecosystem assessment and management process at all stages, including data collection, data management, data analysis and modeling, and presentation of results.

2.1 Data Collecting, Preprocessing, Storage, and Management

Large amounts and diverse sorts of data may be required for environmental modeling. Due to the nature of the environmental management problems, much of these data have spatial characteristics. For example, land use and land cover data, digital elevation models, and remote sensing imagery provide useful information to those attempting to model environmental and ecological processes. Geomatics provides a convenient means of collecting, storing, and managing such data. Steyaert and Goodchild [3] noted that Geomatics has automatic “housekeeping” functions, such as builds the inventory of data layers, and provides consistent access to diverse data that have been integrated into the system.

GIS is able to build the inventory of data for modeling the ecosystem, whether the modeling procedure is in a GIS or an external environment. GIS has the function of integrating historic, socioeconomic, and environmental data, which allows users to identify properties to conduct ecosystem assessments and rank properties and determine priorities. A well-defined geodatabase can record multiple types of information about an ecosystem, such as geographical location, area, zoning, functioning factors, development history, and infrastructure. GIS also provides compatible data services for external packages (e.g., simulation modeling packages) by reformatting and exporting data into desired format. GPS provides biologists and managers with the ability to collect accurate locational information in the field, which can be related and integrated with other spatial data using GIS.

Remote sensing has been used as the primary data source for detecting land cover and land use condition, mapping the extent and providing ancillary data for ecosystems. Moreover, remote sensing provides consistent measurements over the entire area that is not subject to varying data collection methods in different locations. The quality of remote sensing data depends on its spatial, spectral, radiometric, and temporal resolutions. Millennium Ecosystem Assessment [4] lists most remote sensing data that are useful to assess ecosystem conditions from various sensors on satellites (see Table 1).

Table 1 Remote sensing platforms for monitoring land [4]

Platform	Sensor	Spatial resolution at Nadir	Date of observations
Coarse resolution satellite sensors (>1 km)			
NOAA-TIROS (National Oceanic and Atmospheric Administration-Television and Infrared Observation Satellite)	AVHRR (Advanced Very High Resolution Radiometer)	1.1 km (local area coverage); 8 km (global area coverage)	1978–present
SPOT (Systeme Probatoire pour la Observation de la Terre)	VEGETATION	1.15 km	1998–present
ADEOS-II (Advanced Earth Observing Satellite)	POLDER (Polarization and Directionality of the Earth's Reflectances)	7 × 6 km	2002–present
SeaStar	SeaWIFS (Sea viewing Wide Field of View)	1 km (local coverage); 4 km (global coverage)	1997–present
Moderate resolution satellite sensors (250 m–1 km)			
ADEOS-II (Advanced Earth Observing Satellite)	GLI (Global Imager)	250 m–l km	2002–present
EOS AM and PM (Earth Observing System)	MODIS (Moderate Resolution Spectra radio meter)	250–1,000 m	1999–present
EOS AH and PM (Earth Observing System)	MISR (Multi-angle Imaging Spectra Radiometer)	275 m	1999–present
Envisat	MERIS (Medium Resolution Imaging Spectra radio meter)	350–1,200 m	2002–present
Envisat	ASAR (Advanced Synthetic Aperture Radar)	150–1,000 m	2002–present
High resolution satellite sensors (20–250 m)[a]			
SPOT (Systeme Probatoire pour la Observation de la Terre)	HRV (High Resolution Visible Imaging System)	20 m; 10 m (panchromatic)	1986–present
ERS (European Remote Sensing Satellite)	SAR (Synthetic Aperture Radar)	30 m	1995–present
Radarsat		10–100 m	1995–present
Landsat (Land Satellite)	MSS (Multi-spectral Scanner)	83 m	1972–1997
Landsat (Land Satellite)	TM (Thematic Mapper)	30 m (120 m thermal–infrared band)	1984–present
Landsat (Land Satellite)	ETM+ (Enhanced Thematic Mapper)	30 m	1999–present

(continued)

Table 1 (continued)

Platform	Sensor	Spatial resolution at Nadir	Date of observations
EOS AM and PM (Earth Observing System)	ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer)	15–90 m	1999–present
RS (Indian Remote Sensing)	LISS 3 (Linear Imaging Self-scanner)	23 m; 5.8 m (panchromatic)	1995–present
Very high resolution satellite sensors (<20 m)[a]			
JERS (Japanese Earth Resources Satellite)	SAR (Synthetic Aperture Radar)	18 m	1992–1998
JERS (Japanese Earth Resources Satellite)	OPS	18 × 24 m	1992–1998
IKONOS		1 m panchromatic; 4 m multi-spectral	1999–present
QuickBird		0.61 m panchromatic; 2.44 m multi-spectral	2001–present
SPOT-5	HRG-HRS	10 m; 2.5 m (panchromatic)	2002–present

2.2 Spatial Analysis

What make geospatial data more important than non-spatial data is the spatial attribute, based on which the spatial modeling of environment assessment and management can be established. Based on this unique property, GIS can take into consideration of the spatial scale and can integrate the scale theory into ecosystem studies. In addition, the spatial dimension of GIS data can be used to simulate and test spatial hypotheses, which are difficulties most ecologists face while address ecosystem assessment issues.

The spatial analytical functions in GIS consist of a combination of spatial analysis tools, which can work with data in both vector and raster data. For example, data layers in GIS for the same area can be imposed on top of each other to be analyzed for change detection over time. In raster-based GIS, remote sensing products can also be integrated into the analysis procedure. For example, Dahdouh-Guebas [2] analyzed how remote sensing technology and other scientific tools can be integrated in long-term studies, both retrospective and predictive, in order to anticipate degradation and to take mitigating measures at an early stage of a sustainable management of tropical coastal ecosystems. Additionally, GIS can be used to analyze the results of a modeling process. For example, the use of Boolean logical operators and weighted reclassification functions, which are generic to GIS, would facilitate the identification of suitable areas in a multi-criteria analysis.

However, GIS as a stand-alone system is sometimes not sufficient for environmental assessment or management modeling. GIS is commonly combined with other environmental software, but the passing of data from GIS to other software often results in bulky data conversion procedures [3]. On the other hand, more and more GIS packages are equipped with application programming interfaces (APIs). These APIs make it possible for users with programming capabilities to customize or design generic models.

2.3 Visualization and Presentation

A final category of the potential contributions of Geomatics to the ecosystem assessment and management process is the visualization and presentation of results. A chart is worth a 1,000 words, but in geographical studies a map is worth a 1,000 charts. As an important component of Geomatics, cartographic mapping is capable of adding more explanatory and intuitive power to the traditional tabular and graphical reporting formats. The importance of this capability in ecosystem assessment and management is reflected by the persistent reference in the adaptive management literature to the significant communicative role of clear visual presentation of results [5–7].

With the prevalence of Internet and mobile devices, the visualization and presentation of geographical data are not limited to paper-based maps any more.

GIS Web services are the software components that host spatial data and GIS functionalities that can be accessed and integrated into customized GIS applications through the Internet. Developers utilize GIS Web services for custom applications that process geographical information without having to maintain a full GIS system or the associated spatial data [8]. Users can tap into Web-based GIS distribution systems through their Web browsers without having any specialized GIS software on the desktop system. Web-based GIS technologies have also enabled the possibility of using Internet to publish the data from the inventory and GIS database. The focus in this mode of GIS use is not necessary on its geodetic or analytic capabilities (although they do play a major role), but rather on the visual and contextual exploration of the problem situation and issues connected to it.

Web-based GIS also facilitates the procedure of collecting inputs from public in the process of ecosystem assessment and management. The integration of user requirement and user feedbacks is now indispensable in general information systems design [9] and in GIS design [10]. Public Participation GIS (PPGIS) has emerged as a test bed for techniques, methodologies, ideas, and discussion about the social implication of GIS technology. PPGIS enables users to benefit from GIS' ability to bring together many different data sources into comprehensive and manageable format making it an excellent tool for data management. For instance, community groups and citizens can contribute information such as historic land uses, old photographs, or other data that completes the inventory of an ecosystem.

Two key benefits of Web-based GIS distribution systems are the increased interaction with users and connections to a wider audience [11] and its advanced data integration capabilities [12]. Thus, there is potential for more people over a broader area to be reached through the Internet than other forum options and certainly at a lower cost compared to traditional methods—i.e., printing or public forums. In addition, any updates to data can be made on the Web server and are immediately available to users with little or no printing costs.

The second key benefit discussed in the literature is the capability of Web-based GIS distribution systems to relate a wide range of spatial and non-spatial data sets. The systems discussed are used as public forums and as decision support tools for projects from environmental assessments to transportation infrastructure and mass transit routing [8]. These systems can integrate spatially referenced shape files with tabular attribute data, satellite imagery, and aerial photographs. In addition, other photographs, images, and documents along with links to additional Web resources can be incorporated. Common analysis tools also allow users to extract, overlay, and join spatially related data, create buffers and service areas around features, and perform advanced spatial and network analyses.

This Web-based GIS thus allows users to search the repository through selection criteria with a series of menus and query functions to retrieve data results for ecosystem assessment or management. Output is displayed through a combination of text, maps, and digital orthophotographs. This system is thus a comprehensive data delivery tool that can assist policymakers' and stakeholders' with development decisions to encourage sustainable ecosystem management.

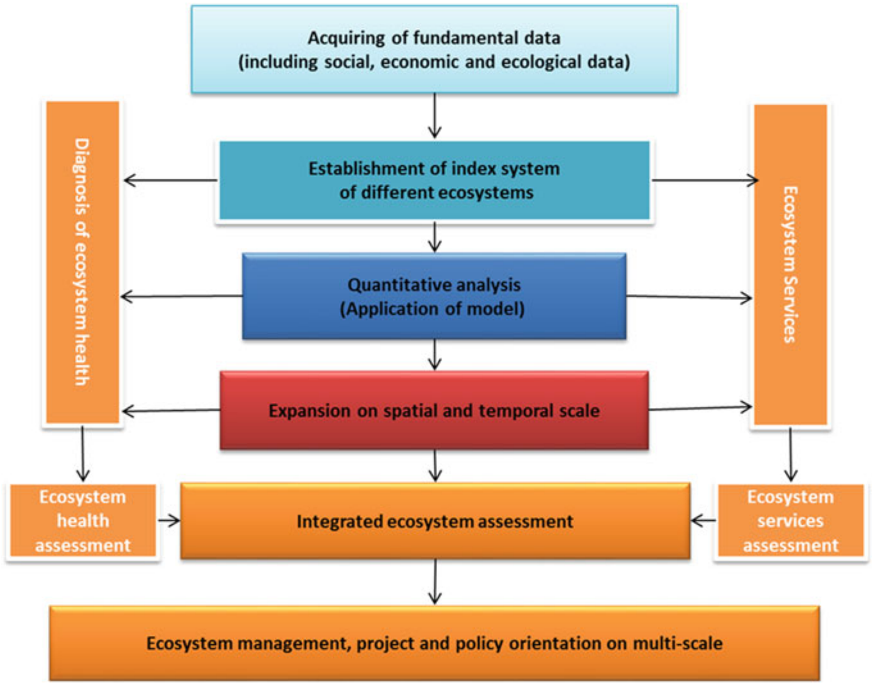

Fig. 1 Framework for ecosystem assessment

3 Practical Framework for Ecosystem Assessment and Management

Ecosystem assessment is a complicated, comprehensive, multi-scale, and dynamic process, which covers knowledge of ecology, geography, economics, and many other related disciplines. In order to find a way to integrate the entire ecosystem attributes from natural, social, and cultural scopes, an integrated ecosystem assessment model is recommended to synthesize the effects of multiple drivers on all ecosystems. Figure 1 servers as a standard procedure of an ecosystem assessment and management project.

Since ecosystem health assessment somewhat includes risk assessment, ecosystem health assessment and service assessment are taken as the subsets of integrated ecosystem assessment. Evaluating different indicators of ecosystem sustainability from two separated perspective, the result of these two methods is required to be integrated to demonstrate a synthesized condition of the ecosystem.

3.1 Required Geomatics Techniques of Practicing the Framework

3.1.1 Graph-Theoretic Analysis Methodology

Since drivers or indicators may interact with each other and have a combined effect on ecosystems, it is important to understand not only the impacts of drivers upon the ecosystem itself, but also the interactions among drivers. Therefore, it is essential to figure out a way to identify and weigh the relationships among drivers.

A graph-theoretic analysis methodology is developed by Wenger et al. [13] to identify the relationships among ecosystem change drivers. It is required at first to identify a list of drivers affecting the ecosystem under study. A matrix is then constructed in which the relationship between each pair of drivers in this list is identified. Specifically, a determination must be made to measure whether the first stressor in a given pair has an augmenting, a diminishing, or no impact on the second stressor in the pair. Both the construction of the list of drivers and the determination of the relationships between each pair of drivers must be reinforced by the best information contained in scientific journals and reports. An effective way to interpret the available scientific information required to make these decisions is to employ, for example in a workshop setting, the scientific expertise of persons acquainted with the ecosystem under study.

3.1.2 Multi-Criteria Evaluation

In an integration process, different indicators are evaluated according to weighted criteria, resulting in a ranking on a suitability scale. Usually, several criteria will be required and be evaluated all together in order to meet a specific objective. Such a procedure is called Index Overlying or multi-criteria evaluation (MCE). MCE is in fact a weighted linear combination of all indicators or factors by applying a weight to each followed by a summation of the results to yield a suitability or risk assessment (see Fig. 2).

The most commonly used method is multi-linear weighted model. The basic model is

$$I = \sum_{i=1}^{m} W_i \left(\sum_{j=1}^{m} W_{ij} P_{ij} \right),$$

where W_i is the weight of the ith factor, W_{ij} is the weight of jth indicator in the ith factor, P_{ij} is the standardization value of the weight of jth indicator in the ith factor, and I is the synthesis index of ecosystem condition.

The basic procedure is as follows: firstly, to (1) establish the indicators system according to the object of assessment, then (2) determine the weight of each indicator and standardize these indicators, and finally (3) assess the ecosystem

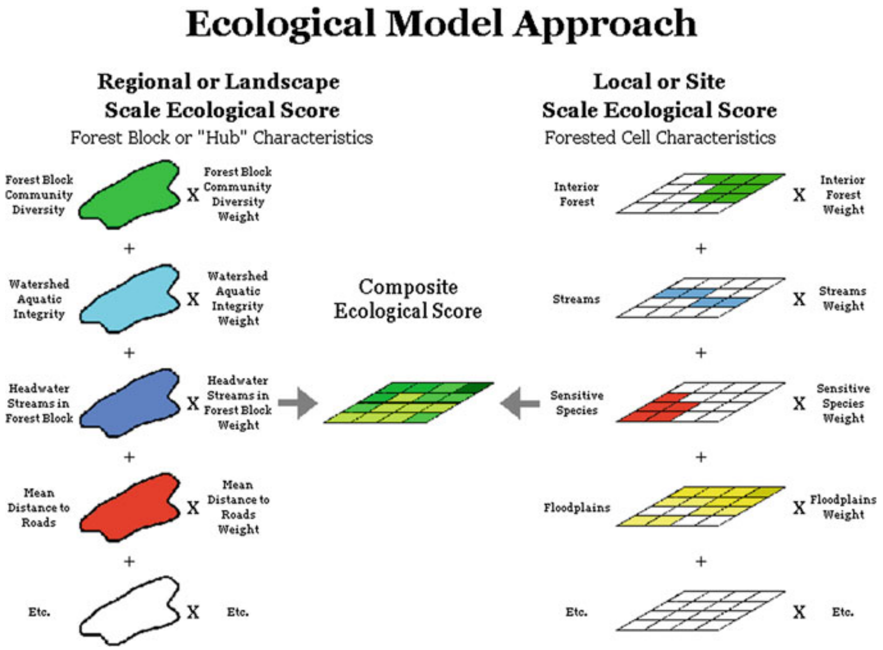

Fig. 2 Example of the process of index overlay. *Source* http://www.dnr.state.md.us/forests/planning/sfla/images/ecol_apph.gif

synthetically with respect to the assessment model. Based on fundamental model, several ameliorated models have been generated with the introduction of fuzzy sets and multi-criteria theories [14–16].

3.1.3 Fuzzy Logic Approach

Conventional approaches for assessing ecosystems are based on crisp sets for indicators of ecosystem health or services, such as population, regional GDP, biodiversity, and environmental quality. Defining a crisp sets for attributes of an ecosystem is based on the assumption that it is possible to make a sharp, unambiguous distinction between an ecosystem that is healthy and one that is comparably not so healthy. However, due to the uncertainties inherent in ecosystem assessments, defining thresholds for those attributes is arbitrary and could give rise to faulty or misleading conclusions. An alternative approach for evaluating strong sustainability is proposed by Prato [16] that uses fuzzy sets to develop fuzzy propositions about ecosystem attributes and strong sustainability and applies fuzzy logic to evaluate those propositions. Due to fuzzy logic's ability to resolve ambiguity, it is able to process an input space to an output space through a mechanism of if–then inference rules. Fuzzy logic techniques in the form of approximate reasoning offer powerful reasoning capabilities for decision support and expert systems [17].

According to Prato [16], evaluation of the an ecosystem in terms of sustainability requires the manager to (1) specify the prior probability the ecosystem is strongly sustainable; (2) define fuzzy sets for combinations of attribute values and probability qualifiers; (3) estimate the joint frequency distribution for ecosystem attributes; and (4) develop a rule for inferring strong sustainability from fuzzy propositions.

4 Conclusion

In conclusion, studies of both ecosystem assessment and ecosystem management can benefit from the very rapid advances in geospatial technology in the past decades. Geomatics has been successfully applied in biodiversity assessment, wetland mapping, drylands degradation assessment, measurements of land surface and marine attribute, and many other applications, as inputs to ecosystem assessment and management models. Wang et al. [18] and Yang [19] applied remote sensing and GIS in the spatiotemporal dynamic analysis of land use/cover change by using post-classification comparison and GIS overlay techniques. Bydekerke et al. [20], Ceballos-Silva and Lopez-Blanco [21], and Kalogirou [22] all have used GIS techniques to identify suitable areas for crops, MCE approach and fuzzy membership function were also used to generate standardized factor maps. RS and GIS environment was also applied successfully to anticipate degradation and to take mitigating measures at an early stage [2]. The quality of life (QOL) of could also be assessed by integrating environmental variables extracted from Landsat thematic mapper data with socioeconomic variables obtained from the Census data, in which principal components analysis (PCA) method was used [23].

The development of Geomatics in recent years has been revolutionized by rapid advances in computer hardware and software. Despite the technical advances in Geomatics and the expanding applications in research, there are still a number of fundamental issues that remain unaddressed when using Geomatics techniques. For example, there is little theoretic consideration of finding the most appropriate spatial resolution (scale) for remote data while considering the domain of the study area. In addition, GIS still lacks many statistical functions. Users often have to use external statistical software in order to run some statistical analysis.

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