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Remote sensing and GIS application in agriculture and natural resource management economics

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ABSTRACT

Agricultural production systems are highly vulnerable to variations in climate, soil and topography of different regions. For sustainable agricultural management, all these factors need to be analyzed on spatio-temporal basis. The advanced techniques like remote sensing, global positioning system and geographical information system can be of great use for their assessment and management. Remote sensing and GIS are very important tools having wide range of applications to tackle these issues. These technologies have manifold applications in agriculture including crop discrimination, crop growth monitoring/ stress detection, crop inventory, soil moisture estimation, computation of crop evapo-transpiration, site-specific management/ precision agriculture, crop acreage estimation and yield prediction. Timely and reliable information on crop acreage, growth condition and yield estimation can be highly beneficial to the producers, managers and policy planners for taking tactical decisions regarding food security, import/export and economic impact. Such information on regional basis can be made available with the use of remote sensing and GIS techniques. Remote sensing and GIS can also be used very effectively in land use/ land cover analysis as well as damage assessment because of drought, floods and other extreme weather events An attempt has been made in the present study to review, analyses and evaluate the latest information regarding the application of remote sensing techniques for crop monitoring, crop condition assessment and yield estimation for sustainability of agriculture and natural resources under changing climatic scenarios. Remote sensing and Geographical Information System (GIS) offers an abundant opportunity to monitor and manage natural resources at multi-temporal, multi-spectral and multi-spatial resolution. It is an urgent need to understand the specialized capabilities of an ever-expanding array of image sources and analysis techniques for natural resource managers. In this review, we compile the various applications of remote sensing and GIS tools that can be used for natural resource management and economic. The information is useful for the natural resource managers to understand and more effectively collaborate with remote sensing scientists to develop and apply remote sensing science to achieve monitoring objectives.

KEYWORDS

Remote Sensing, Geographical Information System, Sustainable Agricultural, Management, Economic

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Remote Sensing and GIS Application in Agriculture

In recent years, remotely sensed data has been widely used for its application in various natural resource management disciplines. With the availability of remotely sensed data from different sensors of various platforms with a wide range of spatiotemporal, radiometric and spectral resolutions has made remote sensing as, perhaps, the best source of data for large scale applications and study.

The exhaustive data provided by remote sensing is now serves as an input data for several environmental process modeling). The integrated use of remotely sensed data, GPS, and GIS will enable consultants and natural resource managers and researchers in government agencies, conservation organizations, and industry to develop management plans for a variety of natural resource management applications.

It is a potential tool to study change in land cover, forest density, coastal morphology, status of reef and biodiversity of islands even if, located in remote place. Agriculture in third world is hindered due to small land-holdings, inadequate resources and lack of agro-technological information. Under the changing climatic scenarios, agricultural planning and use of agricultural technologies need precise spatio-temporal meteorological and crop information for accurate data analyses, forecasts and their effective application in agricultural planning and management decisions, irrigation scheduling, crop stress management and preparedness for calamities and sustainability of natural resources and ecosystems over different regions. The broad objective of sustainable agriculture is to balance the inherent land resources with crop requirements, paying special attention to optimization of resource use towards achievement of sustained productivity over a long period. Although the conventional methods of acquiring weather and crop growth status information are reliable, but they are labor intensive and time consuming. However, recently remote sensing (RS) and geographical information system (GIS) technologies are gaining importance for acquiring spatio-temporal meteorological and crop status information for complementing the traditional methods.

Remote sensing data can greatly contribute to the monitoring by providing timely, synoptic, cost-efficient and repetitive information about the earth's surface (Acharya *et al*., 2018). Remote sensing provides a cheap alternative for data acquisition over large geographical areas. Remote sensing along with GIS is highly beneficial for creating spatial-temporal basic informative layers and generating valuable integrated information by superimposing different basic layers. This technology can be successfully applied to diverse fields including floodplain mapping, hydrological modeling, and surface energy flux, urban development, land use changes, crop growth monitoring and stress detection. Today, remote sensing is potentially a practical management tool for site-specific crop management in precision agriculture. Keeping in view the importance of remote sensing and GIS technology under changing climatic conditions, the relevant literature on application of remote sensing and GIS for sustainability of agriculture and natural resources is reviewed and reported in the present manuscript.

Agricultural Water Management Using Remote Sensing

Food and water security are among the biggest challenges that many countries are facing. Agricultural water management is an emerging application of remote sensing and there have been many developments in the last two decades. The applications include water use monitoring to irrigation performance assessment using satellite data.

To improve water use efficiency it is very critical to monitor the water use at different scales, most importantly at a basin scale where water allocation to different sectors takes place. The biggest share of water (around 70 %) is often allocated for irrigation. Hence monitoring the spatial and temporal dynamics of water availability, irrigated area and water use at basin level will play a big role in ensuring proper allocation of water in a sustainable way. Many developing and under-developed countries lack ground based monitoring systems which are of high maintenance. The water professionals often working in Non-governmental and governmental sectors in these countries often don't have the required know-how in applying advanced remote sensing techniques to extract information from pixels.

In this context developing the capacity of the professionals working in this field to make use of geospatial technology to apply in agricultural water management is highly relevant. These capacity development initiatives has to be promoted extensively in form of short courses or tailor made trainings following the "pixel for people" concept. The impacts of such educational initiatives are much more visible in short time with project uptakes and partner networking (Atzberge, 2013).

Application in Agriculture

There has been increased emphasis on the potential utility of using remote sensing platforms to obtain real time assessments of the agricultural landscape. Precision agriculture is a production system that promotes variable management practices within a field, according to site conditions. This system is based on new tools and sources of information provided by modern technologies. These include the global positioning system (GPS), geographic information systems (GIS), yield monitoring devices, soil, plant and pest sensors, remote sensing, and variable rate technologies for applicators of inputs.

Satellite remote sensing, in conjunction with geographic information systems (GIS), has been widely applied and been recognized as a powerful and effective tool in detecting land use and land cover change. It provides cost-effective multi-spectral and multi-temporal data, and turns them into information valuable for understanding and monitoring land development patterns. GIS technology provides a flexible environment for storing, analyzing, and displaying digital data necessary for change detection and database development. Satellite imagery has been used to monitor discrete land cover types by spectral classification or to estimate biophysical characteristics of land surfaces via linear relationships with spectral reflectance's or indices (Atzberger, 2013).

Application in Soil Science

In nature soil properties are spatially variable therefore it should be estimated as continuous variable rather than point values to have higher accuracy and wide applications. Further, the traditional method of soil analysis and interpretation are laborious, time consuming, thus becoming expensive and its variants have become widely recognized as an important spatial interpolation technique in land resource inventories. In this context, with the advancement of geographical information system (GIS) and remote sensing technology, predictive soil mapping techniques have been developed. The in situ point measurements of soil quality can be made a regression analysis with exhaustive satellite derived indices and the correlation is upscale to larger areas spatially. The spatial maps are also an ideal input for spatially distributed models. The vegetation cover, slope and erosion status derived from remote sensing data to delineate four major land degradation categories *viz*., under degraded, moderately degraded, degraded and severely degraded. Similarly remote sensing and GIS was successfully used for natural resource mapping and soil taxonomic study by (Baret *et al.*, 2007).

Application in Crop-Irrigation Demand Monitoring

Agriculture is the major consumer of water, utilizing more than 70% of the global fresh water. Hence, the role of irrigation water plays a significant part in increasing land productivity. Land surface evapotranspiration (ET) is one of the main components of the water balance that is responsible for water loss and it is of prime interest for environmental applications, such as optimizing irrigation water use, irrigation system performance, crop water deficit, etc. Also, poor irrigation timing and insufficient applications of water are universal factors that limit agriculture production in many arid and semi-arid agricultural regions. In the context of these problems, remote sensing technology has been emerged as an effective tool to monitor irrigated lands over a variety of climatic conditions and locations over the last few decades. It helps in determining when and how much to irrigate by monitoring plant water status, by measuring rates of evapotranspiration and by estimating crop coefficients. The effective use of surface water and the monitoring of consumptive use of water using remote sensing techniques has been a topic of great interest for irrigation water policy makers.

Application in Crop Modeling

It is possible to combine crop models and remote sensing in the way of evaluate yield variables from remote sensed data for each time step in the model simulations, thus the use of remote sensing allows us to fill the missing model parameters during the recalibration in field scale. Additionally, getting data from crop models in field scale -remote sense allows transferring the results from field scale to regional scale. Many ways of using remote sensing data with crop models have been suggested. One way is estimating LAI (leaf area index) values by remote sensing for calibrating into the crop models. Other way is early estimates of the final yield but this method needs many remote sensing data during the growing season to use in crop models. The combined remote sensing observation with crop models for providing stress quantification through assimilation approaches. Crop and soil model with GIS can be used to detect methane emission from fields similarly it is used to estimate global food production and the impacts of global warming using GIS and crop model. There are several ways to reduce crop model uncertainty with remote sensing. One possibility is remote sensing images can be used classify agricultural fields and crop types, In this way crop models can be selected to use with this classification corresponding to soil input data. Remote sensing can also be used to estimate crop growth indicator that can be integrated with crop models (Longley, *et al*., 2001).

Application in Water Resource Management

Water as a resource is essential to support human existence. The availability of fresh water for human use has been declining over the years, whereas the demand of growing population is increasing. In this context, there is an urgent need to monitor and obtain a better understanding of its use, which will provide information that can assist towards the development of effective water management strategies and infrastructures. This can be of crucial importance, particularly to regions on which the amount of water available is limited. Understanding the complex water system requires a holistic approach to integrate the concepts and ideas from different disciplines for sustainable water resource management (Stimson *et al*., 2005). A field scale study brings first insights to develop a detailed understanding about the manifold processes of the water cycle. However, the political decisions are made at regional to national level and thus it is crucial to reasonably upscale field scale studies to regional or national level. Hydrological models are generally used for this purpose but often suffer problems of data scarcity or lack of quality input data. Remote sensing technologies would then be a promising tool to integrate with the models for getting continuous input data in data scarce regions. The launch of several Earth Observation (EO) sensors from advanced satellites provides world-wide continuous measurements on various hydrological components which are essential input data for hydrological modeling.

The data gaps due to lack of on-the-ground monitoring of water resources around the world are now available using satellite acquisition. Thus, satellite products and sophisticated computational techniques for the management of water can play an important role in present and future of water resources. The satellite remote sensing for hydrological applications includes, but not limited to rainfall (Global Precipitation Measurements (GPM) and Tropical Rainfall Measuring Mission (TRMM); Soil moisture (Soil Moisture Active Passive (SMAP) and Soil Moisture Ocean Salinity (SMOS); Actual Evapotranspiration (Surface Energy Balance System); Mapping Evapotranspiration with Internalized Calibration (METRIC) and Surface Energy Balance Algorithm for Land (SEBAL); Groundwater level monitoring by Gravity Recovery and Climate Experiment (GRACE). Using satellite data and GIS, water bodies such as rivers, lakes, dams and reservoirs can be mapped in 3D. The spatial water availability maps can be generated. The concerned authorities can use the information for identifying the sites or regions that need effective protection and management and decisions can be made regarding the sustainable management of water resources in the identified regions (Lee *et al*., 2010).

Application in Water Quality Monitoring

Regular monitoring of water quality is required to manage and improve the quality for human consumption purpose. In situ measurements and laboratory analysis of water samples are currently used to evaluate water quality. Though such measurements are accurate for a point in time and space, they do not give either the spatial or temporal view of water quality needed for accurate assessment or management of water bodies. Furthermore they are expensive and time consuming and cannot satisfy the regional or national monitoring need. Remote sensing techniques can be used to monitor water quality parameters (i.e., suspended sediments (turbidity), chlorophyll, and temperature).

Optical and thermal sensors on boats, aircraft, and satellites provide both spatial and temporal information needed to monitor changes in water quality parameters for developing management practices to improve water quality. Remote sensing has been also used to measure chlorophyll concentrations spatially and temporally based on empirical relationships with radiance or reflectance. The empirical relationships (algorithms) between the concentration of suspended sediments and radiance or reflectance for a specific date and site were developed to predict the water quality for several years (Bernardes *et al*., 2012).

Forest Management and Wildlife Habitat Analysis

Forest is a vital organ of our ecosystem; they impact human lives in several ways, despite of having huge. Importance the world forest has been declining at an alarming rate. Being a renewable resource, forest cover can be regenerated through sustainable management. Hence, using remote sensing data and GIS techniques, a forest manager can generate information regarding forest cover; types of forest present within an area of interest, human encroachment extent into forest land/ protected areas, encroachment of desert like conditions and so on. This information is crucial for the development of forest management plans and in the process of decision making to ensure that effective policies should put in place to control and govern the manner in which forest resources can be utilized. The suitability and status of sites/ forest area for a particular species of wildlife can also be assessed using remote sensing data using multi criteria analysis.

Application in Natural Disaster Management

Extensive multi-temporal spatial data is required for the management of natural disasters such flooding, earth quakes, volcanic eruptions and landslides. In this context satellite remote sensing is an ideal tool that offers information over large areas and at short time intervals, which can be utilized in various phases of disaster management, such as prevention, preparedness, relief, reconstruction, early warning and monitoring. Along with remote sensing, GIS techniques are required to handle huge spatial data sets and hence have been gaining importance in disaster management.

Physiological Studies

Remote sensing data have been exploited to estimate canopy characteristics by using empirical approaches based on spectral indices. Different properties such as plant density, leaf area index, chlorophyll content etc. can be estimated using hyper spectral imagery. These studies investigated the spectral reflectance properties of the plants, identifying key spectral wavebands related to specific plant physiological and structural characteristics, hence deriving sensitive vegetation spectral indices for their non-destructive estimation. Analysis of hyper spectral remote sensing data has been carried out to estimate for agricultural crops and forests. Several narrow and broad band vegetation indices in order to explore the possibility of hyper spectral data to improve the estimation of biophysical variables, canopy crown and crown volume when compared to multispectral analyses (Hall *et al*., 2003).

The spectral and spatial information content of the satellite data was exploited to validate canopy reflectance models. Results obtained for the crops under investigation encourage the use of canopy reflectance models in the inverse mode in order to retrieve other vegetation parameters such as chlorophyll content, dry matter and canopy geometrical characteristics like mean leaf inclination angle. The accurate estimation of plant water status and plant water stress is essential for the integration of remote sensing into precision agricultural and forestry management. The potential to spectrally estimate plant physiological properties over relatively large areas, and to predict plant water status and plant water stress has been demonstrated for agricultural crops and forestry species. These studies indicated the potential use of vegetation spectral indices derived from various scales of remote sensing data for determining plant physiological properties and improving estimates of plant physiological and structural characteristics from hyper spectral data, allowing for much more detailed spectral analyses and hence more accurate estimates.

Monitoring of Vegetation Status

Remote sensing of soil and crop can be an attractive alternative to the traditional methods of field scouting because of the capability of covering large areas rapidly and repeatedly providing spatial and temporal information necessary for sustainable soil and crop management. The potential of remote sensing in agriculture is very high because of its ability to infer about soil and vegetation cover as a non-destructive mean. Numerous spectral vegetation indices (VIs) have been developed to characterize vegetation canopies. A most significant intellectual challenge to ecologists and bio-geographers is to understand spatial-temporal patterns of vegetation. While tracing the footprint of vegetation dynamics modeled a relationship between Advanced Very High Resolution Radiometer (AVHRR) / Moderate Imaging Spectro-radiometer (MODIS) NDVI and rainfall using regression analysis. Results showed a high correlation between rainfall and NDVI which proved that vegetation trend monitoring with RS and GIS can give accurate indication of climate change. Carbon stock within the two classes were calculated and linked to a multi-temporal set of SPOT satellite data acquired in 1991, 2004 and 2009 together with forest prediction for 2020 for the study area (Diallo *et al*., 2009).

Precision Agriculture

Remote sensing technology is a key component of precision farming and is being used by an increasing number of scientists, engineers and large-scale crop growers. Precision farming aims at reduced cost of cultivation, improved control and improved resource use efficiency through information received by the sensors fitted with the farm machineries. Variable rate technology (VRT) is the most advanced component of precision farming. Sensors are mounted on the moving farm machineries containing a computer which provides input recommendation maps and thereby controls the application of inputs based on the information received from GPS receiver.

Nutrient and Water Stress

Nutrient and water stress management is one of the most important fields where we can opt for application of remote sensing and GIS through the application of precision farming. Detecting nutrient stresses using remote sensing and GIS can help in site specific nutrient management and thereby can reduce the cost of cultivation as well as increase the fertilizer use efficiency. In the semi-arid and arid regions, judicious use of water can be possible through adaptation of precision technologies. For example drip irrigation coupled with information from remotely sensed data such canopy-air temperature difference can be used to increase the water use efficiency by reducing the runoff and percolation losses. Development in remote sensing data acquisition capabilities, data processing and interpretation of ground based, airborne and satellite observations have made it possible to couple RS technologies and crop management systems to improve nutrient and water use efficiency. The spectral reflectance in the visible region was higher in water stressed crop than the non-stressed. The vegetation indices like NDVI, RVI, PVI and GI were found lower for stressed and higher for non-stressed crop (Felipe et al (2006).

Pest Infestation

The remote sensing approach in assessing and monitoring insect defoliation has been used to relate differences in spectral responses to chlorosis, yellowing of leaves and foliage reduction over a given time period assuming that these differences can be correlated, classified and interpreted. The range of remote sensing applications has included detecting and mapping defoliation, characterization of pattern disturbances etc. and providing data to pest management decision support system. The possibility of forecasting and vulnerability of forest tress to insect defoliation has also been reported as tool for timely management. The different types of vegetation indices on Landsat imagery acquired before and after defoliation to differentiate between healthy and unhealthy vegetation cover. By used Landsat multi-temporal change detection approach to map defoliated forest of Canada which showed similar results with other studies being carried out.

The extent and severity of gypsy moth infestation in Virginia using imagery acquired by SPOT. Insect defoliation outbreak has also been studied using MODIS data. The MODIS data represent an important tool for insect damaged defoliation and determination of vegetation indices in plot scale (Mee *et al*., 2017). Remote sensing technology as an effective and inexpensive method to identify pest-infested and diseased plants. They used remote sensing techniques to detect specific insect pests and to distinguish between insect and disease damage on oat. They suggested that canopy characteristics and spectral reflectance differences between insect infestation damage and disease infection damage can be measured in oat crop canopies by remote sensing.

Weed Identification and Management

Based on the variation in spectral reflectance characteristics of weeds and crops, remote sensing technology provides a means of identification of weed infestation in the crop stand and further aids in the development of weed maps by detecting the location of weeds within an agricultural field, so that site-specific/need based herbicide can be applied. The higher radiance ratio and NDVI values in solid stand or pure wheat and minimum under solid weed plots. It was observed that by using radiance ratio and NDVI, pure wheat can be distinguished from pure populations of *Rumex spinosus* beyond 30 DAS. Different levels of *Rumex* populations could be discriminated amongst themselves from 60 DAS onwards.

Water Resource Management

In the recent decades, the scarcity of water resources is being experienced at global and regional level and, therefore, needs to be managed judiciously by applying the state of the art technologies. Remote sensing is one of the effective tools for assessing and monitoring the water resources. This technology has been widely used in water resource applications and in particular, hyper spectral remote sensing is emerging as the more in-depth means of investigating spatial, spectral and temporal variations in order to derive more accurate estimates of information required for water resource applications. The advent of microwave remote sensing has made possible the assessment of soil moisture availability from remote sensing data (Folhes *et al*., 2009).

Flood Monitoring

Satellite remote sensing allows timely investigation for large regions and provides frequent imaging of the region of interest.

Until recently, near real-time flood detection was not possible, but with sensors such as Hyperion on board the EO-1 satellite, this has been significantly improved. Automated spacecraft technology has reduced the time to detect and react to flood events in a few hours. Advances in remote sensing have resulted in the investigation of early warning systems with potential global applications. Most recent studies from NASA and the US Geological Survey are utilizing satellite observations of rainfall, rivers and surface topography into early warning systems by employing satellite microwave sensors to gauge discharge from rivers by measuring changes in river widths and satellite based estimates of rainfall to improve warning systems (Wang and Cribb, 2006). The detected flooded areas with satellite data and investigated moisture classes in flood plain areas in relation to water changes, accumulation of sediments and silts for different land-use classes and erosive impacts of floods. Also estimated discharge and flood hydrographs from hydraulic information obtained from remotely sensed data. Optimization methods were also used to minimize discrepancies between simulations and observations of flood extent fields to estimate river discharge.

Estimation of Evapo-transpiration

Estimation of evapotranspiration (ET) is essential for water resource management such as water and energy balance computations, irrigation scheduling, reservoir water losses, runoff prediction, meteorology and climatology. Estimation of spatial variability in evapo-transpiration is possible over a wide area by using remotely sensed information coupled with surface energy balance algorithms. The energy emitted from cropped area has been proven beneficial in assessing crop water stress as the temperature of most plant leaves are mediated by soil water availability and crop evapo-transpiration. The estimated evaporative fraction (EF), defined as the ratio of ET and available radiant energy, by successfully using AVHRR and MODIS data. Several studies have been conducted using more detailed hyper spectral data, ancillary surface data and atmospheric data for improved spatial ET estimates (Batra *et al*., 2006). The availability of water, radiant energy and the removal of water vapour away from the surface are the major factors that control ET. However these factors in turn depend on other variables such as soil moisture, land surface temperature, air temperature, and vegetation cover, vapour pressure, and wind speed which may vary between regions, seasons, and time of day. Generally these factors are accounted for by using a combination of remote sensing data, ancillary surface data and atmospheric data for the estimation of ET values and has lead to extensive measurements of surface fluxes, meteorological and soil variables.

The successfully estimated ET based on the extension of the Priestly-Taylor equation and the relationship between remotely sensed surface temperature and vegetation spectral indices. The combination approach of remote sensing and process modeling produced better predictability of water consumption in irrigated agriculture, and hence improved water resource management in irrigated areas. The combined Landsat7 ETM+ images and derived distributed data such as sowing dates, irrigation practices, soil properties, depth to groundwater and water quality as inputs in exploring water management options during dry season. They revealed that under limited water conditions, regional wheat yield could improve further if water and crop management practices are considered simultaneously and not independently.

Climate Change Scenarios

Since climate is determined by a complex set of physical, chemical, and biological elemental interactions among the atmosphere, the hydrosphere and lithosphere, making understanding and forecasting climate change a challenging task. The climatic conditions on the earth have been and will ever be changing. Amid the dire warnings of severe weather perturbations and global warming, scientists and policy makers have been searching for ways to tackle the threats of climate change. It is therefore, pertinent to understand the dynamic influence of climate perturbations in these spheres both in real time and at synoptic level. Human adaptation for such challenges will require a synergy of data collection and analytical methods which are capable of capturing and processing data at a faster rate. Under such conditions, remote sensing and GIS have found wide applications in climate change analyses and adaptations. Remote sensing enables the acquisition of large-scale comprehensive datasets whereas GIS provides a means of displaying, overlaying, combining data from other sources and analyzing the data. The large collection of past and present remote sensing imageries makes it possible to analyses spatio-temporal pattern of environmental elements and the impact of human activities in past decades. For climate change analysis, remote sensing is a required tool for up-to-date environmental data acquisition both at local and synoptic levels. Scientists are now using satellite instruments to locate sinks and sources of CO_2 in the ocean and land. GIS on the other hand has a very important role to play in environmental monitoring and modeling for combining distributed field-based measurements and remotely sensed data (Larsen, 1999). The climatological and meteorological phenomena are naturally spatially variable, and hence GIS represents a useful solution to the management of vast spatial climate datasets for a wide number of applications (Chapman and Thornes, 2003).

Atmospheric Dynamics

Among other applications, early civilian satellite instruments were launched largely to meet the needs of weather forecasting. Meteorological satellites are designed to measure emitted and reflected radiation from which atmospheric temperature, winds, moisture, and cloud cover can be derived. The remote sensing can be used for the determination of the atmospheric radiances, emissivity and surface temperature. The measured of the absorption cross-sections of NO_2 using the global ozone monitoring experiment (GOME), which are important as accurate reference data for atmospheric remote-sensing of NO_2 and other minor trace gases. On took a time series assessment of global temperature over land and ocean using three surface temperature records and two lower-troposphere temperature records based on satellite microwave data. All the five series showed consistent global warming trends. These results indicate that remote sensing and GIS can be used effectively for global/ regional climate change analysis (Basso *et al*., 2004).

Environmental and Resource Economics

Environmental and resource economics are, by their very nature, intimately concerned with space. The questions these disciplines ask either explicitly or implicitly invoke the spatial dimension. However, the answers provided by economic analyses are frequently naïve regarding the incorporation of this dimension within studies. This article examines the contribution which Geographical Information Systems, or GIS as they are more usually known, may provide in assisting environ-mental and resource economists to consider spatial complexities within their analyses. A GIS is defined as “a system for capturing, storing, checking, integrating, manipulating, analyzing, and displaying data that are spatially referenced to the earth”. However, use of the term GIS can be confusing. At one extreme it may be employed to describe a piece of soft-ware, examples being Arc-Info, MapInfo, or SPANS. At the other extreme, GIS is sometimes used to refer to operational systems designed to support activities such as traffic management or automated mapping. Within the context of the research environment, the former description is normally more appropriate, and the term is typically taken to comprise a commercially developed software application, along with the data and computer hardware used to run it. In this respect, GIS are the analogue of the numerous other software applications that are available for the analysis of quantitative data. However, in terms of their functionality, the key factor that separates a GIS from these more traditional applications is encapsulated by the final five words of the above definition; GIS are specifically designed for the analysis of data that are spatially referenced to the earth.

Hence their real utility in the research environment arises when geographical or spatial relationships form significant elements in the problem being investigated.

Spatial Analysis and the Role of GIS in Environmental Economics

Space, as a key concept underlying much of economics, has been discovered and frequently rediscovered in mainstream economics. Within the fields of environmental and resource economics, space, in the form of distance, has long played a key role in travel cost recreational demand analyses and hedonic models of property price and is starting to play a more formal role in some resource applications. In this section we discuss how the advanced spatial modeling capabilities recently provided by GIS are beginning to improve such analyses and starting to substantially extend the sophistication of spatially sensitive analyses more generally across the field. We also consider the various ways in which different disciplines tend to encapsulate the influence of space and geography within analyses and the advantages and functionality afforded by GIS are reviewed. The manners in which spatial representations may be generated within packages are also considered and the implications of adopting alternate representations are discussed (Liu *et al*., 2007).

In a paper given an interesting insight into differing interpretations of the analytical role of space that have typically been perpetuated by the econometrics and GIS camps. He noted that when spatial econometricians deal with spatial distributions, they view them as a constraint or some exogenous factor that must be factored out or controlled for. Smith argued that it was rather rare that they were viewed as an explanatory dimension of the issue being studied. It is, however, this latter viewpoint which underpins most GIS applications. The paraphrase of the differing views of the importance of space well. In any modeling approach that uses spatial data, there are two key issues: How to use the data "correctly" and how to use it "creatively". The former refers to issues of spatial econometrics. The latter refers to developing ways of creating insights from spatial data that can be used to improve our understanding of the driving forces behind spatial processes. Indeed, many GIS packages actually provide rather little functionality for the types of operation commonly undertaken by spatial econometricians. It is, perhaps, surprising that environmental economists have not been quicker to appreciate the importance of spatial factors in human and ecological processes; the use of GIS in environmental economics is still a relatively recent innovation, despite the fact that the unrealistic spatial assumptions, implicit or otherwise, made by economists in order to implement their analyses have attracted considerable critical comment.

Certainly a review of the characteristics of many human and ecological processes would suggest that spatial considerations may play an important role in shaping observed phenomena. Although GIS were being adopted by organizations such as utility companies throughout the 1980's and early 1990's, their uptake within academia was rather slower. To some extent, the delays associated with the adoption of GIS may be due to a general disillusionment with quantitative geography that prevailed during that period. This slow uptake by the research community which might be expected to be the early adopters within academia was not surprisingly reflected in a virtual absence of applications in environmental economics. Other negative effects may have resulted from a perception of GIS as simply facilitating the employment, albeit in an easy to use environment, of already well-used techniques that had been previously developed by quantitative geographers. Furthermore, some have suggested that GIS may have been seen as representing a Trojan horse through which quantitative geographers were trying to impose their ideas on the wider research community (Liaghat and Balasundram, 2010).

Just as spatial context can play such an important role in socio-economic processes, so it can be an important driver of the natural processes with which environmental and resource economists are commonly concerned. This is because the spatial arrangement of factors such as habitat, land-cover, or effluent discharges has been shown to have an important, and often dramatic, effect on outcomes such as species diversity, natural assimilative capacity, and nutrient cycling. it is not just the total amount of wetlands in a region that affects assimilative capacity, but also their spatial pattern. Likewise, it is not just the total forested land in a region that matters for species abundance and diversity, but its size, shape, and the conflicting land-uses found along its edges. It the ability to quantify and present these kinds of issues provided by GIS that gives the applications such value. If the theoretical benefits of applying to GIS to tackle research issues in the field of environmental economics are recognized, then the practical implications of using the systems requires some consideration. One major decision that needs to be faced at the start of a GIS project concerns whether to build or buy a database. In the early days of GIS, some form of primary or secondary data collection, usually via the digitization of information from a paper map, was required. Nowadays, such a requirement is far less common, and there are many thousands of datasets available for download from the Internet although the costs of obtaining such data vary substantially. A common problem with data obtained from external sources, such as Internet sites, is that they can be encoded in many different formats.

These formats have evolved in response to diverse user requirements. Many GIS packages are able to directly read files produced in AutoCAD, DWG, DXF, DGN, Shape file, and VPF formats. However, the specific level of support provided for different file formats differs greatly between GIS. A number of organizations have grouped together with the aim of standardizing various aspects of geographical data provision. One organization of particular note is the Open GIS Consortium, a group of vendors, users, and academics interested in the interoperability of GIS. To date, some progress has been made on metadata standards and web access, although the introduction of a common file format that can be used in all GIS packages is still some way away (Tan and Shibasaki, 2003).

The physical data model used to represent the location of entities in a GIS generally conforms to one of two types, either being based on raster or vector representations of real world topology. In the raster data model, an array of cells, or pixels, are used to represent real-world objects. The cells can hold attribute values based on one or more encoding schemes including categories, integers, or floating point values. The raster model is particularly suitable for representing information that has been collected from imaging sources such as aerial photography or satellite remote sensing. It is also an especially appropriate way for depicting phenomena such as temperature, soil type or land-cover that vary continuously throughout space. In contrast, the vector data model is closely linked with a view of objects that possess discrete boundaries. Here the position of entities such as points (e.g., wells, soil pits, houses), lines (e.g., rivers, roads, power-cables) and areas (e.g., census tracts, county boundaries, groundwater protection zones) are defined by sets of co-ordinates which may be separated in the case of points, or joined to form linear or polygonal features.

The vector data model is appropriate for the representation of data that has been digitized from paper maps, and has been widely implemented in GIS because of the precise nature of its representation method, its storage efficiency, the quality of its cartographic output, and the wide range of functional tools that may be employed in its analysis. The specific range of analytical tools that are available in any GIS environment will be somewhat dependent upon both the characteristics of the software package and the data model being used. However, most GIS offer the functionality required to answer a diverse range of spatially grounded questions that are commonly of interest to environmental economists. This diversity is clearly illustrated by the research examples discussed later in this article.

Nevertheless, for the purpose of simplification, the analytical capabilities of GIS that make them particularly useful in this field can be grouped into the seven key categories outlined in Table II. The ability to identify the presence of features at a specified spatial location is of use in numerous analyses, examples being those of land-use change, where the probability of a land parcel being converted to a new function in the future will depend upon the land-cover type currently present. Here the GIS can be used to map conversion probabilities by linking land-cover data with a model of conversion potential (Fleming, 1999). The determination of the location of a certain type of feature also has a wide range of uses, such as for the identification of the spatial distribution of neighborhoods containing toxic landfill sites in studies of environmental equity to pollutant exposure (Reis, 2008).

The ability of GIS packages to quantify spatio-temporal trends in data may be useful in a number of applications such as those concerned with the modeling and prediction of urban growth patterns, whilst the identification of optimal routes through networks like highway systems has obvious applicability for studies using travel cost or hedonic pricing methodologies, where the generation of measures of the spatial accessibility of facilities is important. In such cases GIS can be used to generate indicators of travel times and distances which, if required, may be converted into predictors of travel cost. The identification of patterns in spatial data has important applications in landscape ecology models, where the mosaic of different habitats in an area may be a key predictor of biodiversity. Here, GIS can assist with the calculation of configuration measures such as fragmentation indices. The ability to create buffer zones around features has obvious uses in the delineation of riparian buffers that are designed to intercept and sequester pollutant runoff around streams, lakes, or reservoirs but also has application in the generation of noise contours around road networks.

Similarly the capacity to ask what if types of question can enhance the functionality of virtually any application, from the determination of the likely increase in visitation rate that may be associated with the upgrading of a recreational facility, to the identification of the optimal location for the siting of a new eco-industrial park in order to minimize environmental disamenities from commuting activities (Carr, 1998). Solutions to such location-allocation problems, where the requirement is for the identification of optimal sites based around user specified criteria, are provided by the majority of GIS. Empirical illustration of the functionality afforded by a GIS is provided in the following two sections.

These applications highlight how GIS may be used to combine environmental and other spatial data in the form of digital maps and satellite imagery with more conventional variables to enhance economic models. They also illustrate how the technology may be used to query and visualize model output, for example in the form of maps. It is this dual capacity to improve modeling and display findings that we feel establishes the potential for GIS to significantly enhance many aspects of economic analysis and decision making (Ines *et al*., 2006).

GIS Applications in Environmental Economics

Perhaps the most widespread use of GIS within environmental economic applications is to construct a wide variety of variables for use within hedonic property pricing studies. Hedonic pricing methodologies are well established techniques based on consumer theory which attempt to explain variations in house prices in terms of observed differences in preferences for the attributes of the properties in question. In the case of environmental goods, the aim is to infer a price based upon the marginal variation in property prices associated with their availability. One of the most basic yet important advantages of employing GIS techniques within hedonic property pricing studies is the ability to automatically calculate explanatory variables for a large number of properties enabling a much larger sample size. However, if a GIS only duplicated the procedures used in previous studies then its full potential would not be realized.

Spatial data is increasingly available in digital form and this is enabling property price datasets to be integrated with other spatial information using GIS. A common example is the combination of property price information with census data and the locations of amenities (Shanmugapriya *et al*., 2019). A major advantage of GIS is the ability to perform complex spatial queries on each property. This permits the calculation of variables that would not be possible using any other method. The most common example is the use of car travel times to describe the proximity of an individual property to an amenity. More complex proximity variables can also be created using the GIS. For example, in examining the influence of wetland amenities on sale prices of residential properties in Portland, Oregon, use a GIS to consider the shape of the nearest wetland areas in addition to their proximity. Similarly, for the south coast of England, have approximated forest amenities associated with given property prices by the development of an index variable that measures the ratio of forest acreage to the squared distance away from the home.

The concept further by calculating measures of percent open space, diversity, and fragmentation of land uses around land parcels in the Patuxent Watershed in central Maryland, USA. The authors calculated diversity and fragmentation indices by obtaining 25 class land-cover images from the Maryland Office of Planning. The diversity index was designed to signify the extent to which the landscape was dominated by a few or many land-uses, whilst the fragmentation index was set to represent the variance in landscape parcel types present within an area. Interestingly, the authors found that the marginal contribution of increased diversity and fragmentation to house selling prices was highly context dependent, with a positive association only being observed in the most urbanized areas, possibly reflecting the fact that diversity and fragmentation are valued in these situations as they represent amenities. In a further aid to hedonic studies, GIS can be used to provide information on topography, which may have a profound effect on the influence of local environ-mental attributes as it largely dictates what is visible from a property. Some early hedonic studies included categorical variables to account for the presence of a view of a particular attribute.

For example, used a binary variable to indicate the presence of a river view in suburban dwellings located around the Swan River in Perth, Australia. However, the use of these simple indicators cannot capture measures of quality, such as how much of the attribute is present. Use GIS to calculate of the area of land visible from each property. In more detail later in this article, uses the view shed (a measure of the features that are visible from a viewpoint) functionality of GIS to develop sophisticated, continuous measures of the visibility of various land-uses from residences in Glasgow, Scotland. All of these studies find that the type and (where assessed) the quality of view available from a property is a significant determinant of its price. Although hedonic models are often used to place a value on environmental amenities, they may also be utilized to elucidate the potential costs of environ-mental dis-amenities such as hazardous sites, and air, noise and water pollution. In use a GIS to process traffic and road network data to generate estimates of noise pollution at each property. The impact of proximity to hazardous waste sites on commercial and industrial property values in Fulton County, Florida. They used the ArcView GIS package to calculate the distance each property lay from the nearest hazardous waste site listed on an Environmental Protection Agency database. The grading of each site had an influence on nearby prices; a distance effect was present around sites graded as ‘high risk’ in that there was a negative pressure on surrounding property prices. However, no effect was apparent for low risk sites (Rani *et al*., 2018).

Most hazardous waste sites are clearly visible and their presence is relatively easy to measure. For more subtle indicators of environmental quality like water pollution, it can be difficult to estimate indicators of exposure, and there are relatively few studies in the literature that have investigated these attributes. Despite this, GIS can provide a superior foundation for attempts to calculate such measures. This is illustrated by the work of estimated the potential benefits of a water improvement programmer in Chesapeake Bay based on the development of hedonic models linking prices of waterside properties to indicators of nearby water quality. The research used GIS to assign measures of faucal coliform counts taken at sampling stations to property locations using an inverse distance-weighted average of coliform counts based on data from the nearest monitoring stations. The study found that house prices did exhibit a statistically significant negative association with coliforms, suggesting that the housing market is sensitive to such subtle environmental factors.

Closely associated with the application of hedonic models, the development of methodologies to quantify and priorities the preservation of open spaces has become an important policy topic. A GIS based hedonic pricing model with a theoretical model of how different types of open space are valued by residential owners living close to them. The work showed that permanent open spaces may be three times more valuable to local residents than those which are potentially available for development. Using a case study of Northern Wake County, North Carolina, combined a GIS database of the road network with information on land-cover, property parcel attributes, administrative boundaries, and housing sales. Their analysis confirmed the importance of private open space for property values. The relationship was found to be particularly strong as the stock of open land declined, a result which is consistent with this use serving as a source of open space amenities. Indeed, questions of land-use and land-cover change have attracted interest amongst a wide variety of researchers concerned with modeling the spatial and temporal patterns of land conversion and understanding their causes and consequences. Among them, geographers and natural scientists have taken the lead in developing spatially explicit models of land-use change at highly disaggregate scales. It is unsurprising that GIS has found a role in many recent studies. Here, the main application of the technology has been to facilitate the use of spatial data sets, often produced from remotely sensed sources, that may be used to quantify the spatial distribution of land-uses and, in cases where a time series of data is available, to describe their change (Riedell *et al*., 2004).

Much of the economic work on land use change has focused on deforestation in less-developed countries. For example, develop a simple model of deforestation in Belize using GIS data in which landowners maximize expected profits so that optimal use is determined by the uses with the highest rents. In a more sophisticated analysis, apply Landsat TM satellite data to model tropical deforestation in the southern Yucatan peninsula region of Mexico. They link a GIS based model of landscape change with one founded on survey information gained from inter-views with farmers in order to make comparisons between the predicted and actual deforestation practices of individuals. Other examples of economics models of deforestation using remotely sensed data and GIS include the work. In the urban planning literature provide a spatially explicit and disaggregated land use model. Their unit of observation is a one hectare cell of the landscape, and they use a discrete choice approach to model development and redevelopment in urban settings (Kumar *et al*., 2015).

Outside of developing nations, one of the main centers of research into the application of GIS for the spatially explicit modeling of land use change is at the University of Maryland, USA. Here considerable research has focused upon the Patuxent River watershed, located in central Maryland. The amount of low-density residential land use in this region has increased by 119% between 1973 and 1994. Much use has been made of micro-level GIS data on land and land parcels provided by the Maryland Office of Planning. The dataset contains variables that pertain to individual parcels, including land-use, and GIS has been used to augment this information with a wide variety of additional spatial measures including zoning locations, estimates of distance to urban areas, proximity to services such as public sewers, and indicators of soil quality and terrain steepness.

As part of the Maryland work, they developed a two-stage approach to modeling residential land-use change. An explicit hedonic model was first estimated as a function of spatially varying landscape features, including lot size, accessibility measures, neighborhood zoning, and the percentage of land in different uses. This was used to predict a residential value for all developable land in the region, which was then employed in a binary discrete choice model of land use conversion. The modeling approach can be utilized to predict the effects of different land-use policies. For example, the analyses the influence of a number of alternative land use policies on landscape change, including the effects of different regulatory constraints. A dynamic model of urban-rural fringe development is developed in which land use change over both space and time is considered (Hengl, *et al*., 2004).

The same research group have also embarked upon a range of studies that use similar GIS-based methodologies to investigate the effect of farmland preservation programmers on spatial patterns of preserved, privately owned farmland, and farmland prices. These programmers aim to preserve the amount of farmland in areas where they operate by providing payment to landowners in exchange for the imposition of development constraints that restrict the land from being converted to developed uses by current and future occupiers. The used the Arc-Info GIS package to link 224 individual parcels of farmland sold in three Maryland counties between 1994 and 1997 with data on soil, land-use, and distance to facilities. Contrary to expectations, they found little evidence that voluntary permanent preservations significantly decreased the price of farmland in Maryland, possibly because landowners do not expect land use restrictions to be binding in the future. The under took an analysis of the spatial pattern of preserved land resulting from these preservation programmers. Interestingly, they found that the presence of parcels of preserved land was more associated with areas of low development pressure than with stated policy objectives such as the prevention of urban sprawl.

GIS applications have also been extensively used in numerous recent studies that have investigated the manner in which environmental quality may be maintained by either the targeting of conservation objectives, or the delineation of zoning systems in order to prevent environmental contamination. In many cases, the degree of overlap with the considerations of environmental economists is slight. However, some applications merit attention here. The use GIS to model the optimal riparian buffer to sequester pollutant run-off in the lake. Two models were tested, and the authors found that quantifying the desirability of outcomes based on criteria scoring and pollutant weighting approaches gave rather similar results. In related work, the recently used GIS to investigate the targeting of conservation contracts in heterogeneous landscapes. The term conservation contracting describes the contractual transfer of payments from one party (usually the government) to another (usually the landowner) in exchange for the development of land use practices that contribute to the supply of an environ-mental amenity such as biodiversity. A key issue in the design of conservation contracting initiatives is the manner in which information about spatially variable biophysical and economic conditions may be integrated into a cost-effective conservation plan. Using biophysical and economic data from the GIS system of the City of Syracuse, New York State, an environmental benefit score for conservation initiatives designed to maintain good water quality was calculated for land parcels around Lake Skaneateles.

Each parcel was scored according to its acreage, zoning position, distance to drinking a water intake, area of hydro logically sensitive land, and length of stream frontage. The work found that approaches that incorporate both biophysical and economic data are likely to generate much greater environmental benefits than those that include only one factor. Hence approaches that involve data integration in a GIS should convey considerable benefits (Melesse and Wang, 2007). In order to provide more detail regarding the diverse range of issues which can benefit from the application of GIS techniques, the following section provides a more in-depth insight into a number of studies conducted and ongoing at CSERGE.

Further Applications of GIS to Environmental Economics

The potential contribution of GIS techniques to the aggregation of expressed preference data such as is commonly collected in contingent valuation or discrete choice experiments. Although trivial in terms of the degree of GIS sophistication required, we include this example because we feel that it may help contribute towards improving a generally under-researched yet vital part of the valuation process which can typically induce greater variability into final valuation estimates than do many of the study design issues which commonly fill the pages of many journals. The area of research which has attracted the most wide-spread use of GIS by environmental economists to date; hedonic pricing. Here we show how GIS can contribute to the improved availability and consistent definition of a wide range of the structural, accessibility and neighborhood variables which are the standard fare of any hedonic property price application. However, it is in the definition of environmental variables that GIS promises the most substantial improvement to data availability for such studies. The ability of such systems to quantify spatially defined effects and to generate such data in an automated manner represents a very substantial advance in the practical remit of hedonic applications and permits the extension of the technique into new areas of valuation which had previously involved impractically large data collection budgets. As such we believe that GIS will come to be seen as the standard tool of the hedonic analyst (Part *et al*., 2009). The ability of a GIS to automate and standardize spatial measurement and assessment tasks also provides the basis for its contribution to travel cost assessment of open-access recreation values. In how such routines can not only improve individual applications but also how such standardization and improved access to spatially defined data (including travel cost measures, substitute availability, socio-economic variables, and site quality data) substantially enhances the potential for successful transfer of valuation functions between sites. Amongst a number of such benefit transfer applications we present an application which generates maps of potential woodland recreation benefits across the entire country of Wales, an area chosen for analysis both because of its physical and socio-economic diversity and because long term decline in the dominant agricultural sectors means that the value of farm subsidies far outstrip the value of production making the area ripe for land use conversion into multipurpose woodland. This study area as we examine the timber and carbon sequestration benefits generated through such land-use change. These applications illustrate the use of GIS techniques in bringing spatial realism into analyses and so obviating the need to resort to strong and sometimes debatable assumptions. Our review of empirical applications and contrasts with the cost-benefit focus of preceding sections by considering the role of GIS in providing assessments of the equity of access to environmental quality. While the emphasis here is no longer upon monetary assessment, we show how the spatial outputs of a GIS are directly compatible with those provided in the valuation exercises presented in previous sections and thus allow the decision maker to inspect the consequences for social distribution of differing cost-benefit outcomes and so obtain cost-effective measures of the provision of change to such distributions (Omuto, 2011).

Conclusion

With the rising pressure on natural resources due to the increasing human population, remote sensing and GIS can be used to manage these precious limited resources in an effective and efficient manner. Geospatial information is quite useful in the identification and analysis of factors that affect the utilization of these resources. Hence, with the detailed understanding of these factors, sound decisions can be arrived at that will ensure the sustainable use of natural resources to meet the needs of the current as well as future generations. As demonstrated throughout our review of the literature and empirical studies, the functionality provided by GIS can considerably enhance the incorporation of spatial issues within applied environmental and resource economics. However, it must be emphasized that a GIS is not a universal panacea for improving data analysis. Indeed, the quality of results obtained depends upon a range of factors common to any quantitative analysis, such as the accuracy of the input information, the appropriateness of the data structures used to store it, and the choice of analytical tools employed. In addition the application of GIS introduces a set of new concerns that include issues of spatial representation and data confidentiality.

These matters are significant and warrant some consideration here. Decisions regarding the appropriate spatial data scale, level of data aggregation, and frequency of measurement must be made at an early point in any GIS analysis. These decisions are not trivial, and indeed may have a significant impact on the manner in which the results ultimately obtained can be interpreted. On a theoretical level, the appropriate units for spatial analysis depend upon the questions being asked (Rind fuss and Stern, 1998).

For instance, issues of population travel and migration tend to turn on the decisions of individuals and households, whilst questions of equity of access to environmental quality may require analysis at the scale of neighborhoods. Indeed some problems require consideration at multiple scales. For example, enquiries into changes in land-use and land-cover typically require simultaneous information at the level of the individuals and house-holds that may own the land, the local administration bodies that regulate land-use and make decisions concerning infrastructure, and the regional governments that dictate strategic development strategies. In practice however, the presence of limitations regarding the availability of data often has at least as great influence on the choice of aggregation employed as does any theoretical consideration regarding the appropriateness of different scales. It is our belief that further advances in the computing power and functionality of GIS packages will stimulate development in further areas of environmental economic research in the future. At the moment one particularly active area of development concerns techniques for the production of virtual reality representations from GIS databases. Such Virtual Reality GIS (VRGIS) systems are beginning to be marketed. These allow the two dimensional output of traditional systems to be transformed into three dimensional ‘virtual’ environments which can be viewed or explored by users.

The development of VRGIS opens up the possibility to convey environ-mental information in new ways, and may deliver particular benefits in expressed preference techniques such as contingent valuation and choice experiments where such systems could be used to deliver scenarios depicting the likely future states of environmental goods being considered. Furthermore, a current emphasis on the integration of GIS technologies into World Wide Web sites will open up more opportunities for the sharing of both experience and data, and for the design of new survey methodologies that are able to capture much more heterogeneous samples of individuals that it has been possible to include in the past.

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