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Geo-Spatial Technologies for Carbon Sequestration Monitoring and Management

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Abstract: Problem statement: Globally, the quantification of Carbon Sequestration (CS) potential of various ecosystems was a challenge. There was an urgent need for technologies that can quantify CS potential cost-efficiently in a repeated and organized manner. **Approach:** Remote Sensing (RS) and Geographic Information System (GIS) had great potential in current estimation, future prediction and management of carbon sequestration potential in terrestrial ecosystems. This review discusses the current utilization of RS and GIS technologies in CS management in various sectors. **Results:** Deployment of RS and GIS for CS sequestration improves accuracy, reduces costs, increases productivity and provides current observations from a regional scale. **Conclusion:** This review demonstrates the synergistic role of RS and GIS technologies in improving CS management.

Key words: Remote Sensing (RS), Geographic Information System (GIS), Carbon Sequestration (CS), Precision Agriculture (PA), Decision Support System (DSS),

INTRODUCTION

Climate change is one of the greatest challenges of our time. According to the National Oceanic and Atmospheric Administration of the USA, concentration of CO_2 in the atmosphere has steadily increased from 280 ppm in 1800 to 385 ppm in 2008. This increase has apparently triggered global temperature rise, causing a great deal of discomfort to the world population. The northern hemisphere and the European region are witnessing the disappearance of ice, permafrost, forest fires and fatal heat waves. The southern hemisphere and the Asian region are encountering storms and floods due to overflowing rivers and increased precipitation. Deep and excruciating scars are left behind by natural disasters, affecting the livelihood of various communities. New approaches in climate change mitigation efforts are becoming more important. One such effort is the quantification of Carbon Sequestration (CS) potential of various ecosystems. CS is the process of transfer and secure storage of atmospheric CO_2 into other long-lived carbon pools that would otherwise be emitted or remain in the atmosphere (Lal, 2007). Terrestrial carbon sinks include natural forests, plantation forests, wetlands and the soil biome. Quantification and management of CS in a regional scale would involve the deployment of cutting edge geo-spatial technologies, which are routinely used in Precision Agriculture (PA). PA involves site- and time-specific management of agricultural systems, based on integrated technologies which are able to determine the inputs needed based on localized variations (Balasundram *et al*., 2007). The objectives of PA are to maximize net benefits, in terms of economic, environmental and social goals of the enterprise. PA is enabled by geo-spatial technologies such as geographic information system, global positioning system, optical and proximal remote sensing, geostatistics, artificial neural networks and variable rate technology. These tools can be used in varying configurations to quantify soil status, climatic patterns and crop growth of a certain agricultural system and thrives to lower the production cost by fine-tuning seeding, fertilizer, chemical and water use, which potentially increases production volume and lowers costs (Balasundram *et al*., 2006a; 2006b). These technologies can be potentially used in varying levels of integration for monitoring and management of CS. One

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such approach that is gaining credence in ecological and environmental applications is the integration of remote sensing and geographical information system.

MATERIALS AND METHODS

Remote sensing: Remote Sensing (RS) is the science of obtaining and interpreting information from a distance, using sensors that are not in physical contact with the objects of interest whereas Geographical Information System (GIS) is a system of hardware, software, procedure and personnel to facilitate the management, manipulation, analysis, modeling, representation and display of geo-referenced data to solve complex problems regarding planning and management of resources (Star and Estes, 1990). In principle, RS measures the amount of visible and non-visible radiation reflected from the target surface and is expressed as spectral reflectance Fig. 1. RS platforms include satellites, aircrafts and ground base sensors which can be divided to passive and active sensing. Passive sensors rely on natural source of radiation (i.e., sun) while active sensors generate their own radiation to illuminate its target. RS captures images using multiple stations, bands, dates, stages and polarization and these images can be unified to produce enhanced composite images for analysis, to obtain whole and precise information.

Integration of RS data with GIS: Current RS technology offers acquisition and analysis of geo-referenced data from assorted platforms and can be operationally linked with spatial data layers and models within a GIS. The effortless ability of integrating RS data with other sources of information makes geospatial technology a powerful contemporary instrument (Kohl *et al*., 2006). Likewise, GIS collects and pre-processes spatial data from various sources. It provides the utilities to manage attribute data, location and topology in spatial analyses. Neither RS nor GIS can reach their full potential unless the two technologies are fundamentally linked. At present time, both technologies have revolutionized the facade of modern farming. The interactions of these components were summarized by Wilkinson (1996) as follows:

- RS data can be used as input for analysis within a GIS
- GIS can provide ancillary data for improved RS analysis for discrimination of ecosystem types, land cover and land use classes
- The application of RS and other spatial data within a GIS provides capabilities for modeling and scenario analysis

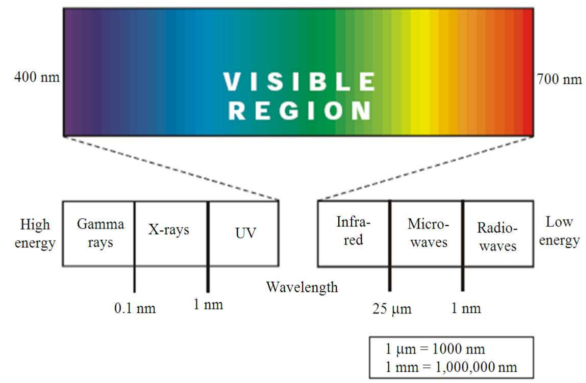

Fig. 1: The visible region within the electromagnetic spectrum, ranging between 400 and 700 nm (Nowatzki *et al*., 2004)

RESULTS

Recent agro-ecological applications of integrated RS-GIS: The integrated RS-GIS approach is well explored and studied in precision farming (Liaghat and Balasundram, 2010; Fitzgerald *et al*., 2006; Seelan *et al*., 2003), aquaculture (Nath *et al*., 2000), crop cultivation (Lopez-Lozano *et al*., 2010), plant nutrient management (Goel *et al*., 2003), forest inventory (Kohl *et al*., 2006), erosion control (Mati *et al*., 2000; Ramos *et al*., 2007), mountain survey (Mulders, 2001), township planning, hydromorphological studies (Chandra and Ghosh, 2006), coastal zone management and assessment of biomass potential from agricultural wastes (Voivontas *et al*., 2001).

In Malaysia, the integrated RS-GIS approach has been employed for evaluation of oil palm crop performance indicators such as inventory of trees phenology, macro-nutrient assessment and replanting (Loh *et al*., 2009). Various workers have exploited high resolution RS platform such as Synthetic Aperture Radar (SAR) and optical sensors for estimation of standing timber volume in forestry .

In Spain, the combined use of Quickbird satellite imagery and digital soil maps facilitated detection of differences in abiotic stress associated with soil sodicity in a 60 ha corn field. Variable rate application based on spatial variability was recommended for operations such as irrigation, fertilization and liming (Lopez-Lozano *et al*., 2010). In Canada, hyperspectral observations using a Compact Airborne Spectrographic Imager (CASI) showed that the spectral reflectance of corn is significantly influenced by weed infestation levels and nitrogen rates (Goel *et al*., 2003).

Integrated RS-GIS for carbon sequestration management and monitoring: Since the Kyoto Protocol, development of Carbon Sequestration (CS) strategies has become a global priority. The Inter-governmental Panel on Climate Change (IPCC) via its Good Practice Guidance Framework encourages the implementation of models and inventory measurement systems that are tailored to address national circumstances. Such models and systems should be driven by high resolution activity data which are disaggregated at sub-national level to fine grid-scales (Goetz *et al*., 2009).

The strength of integrated RS-GIS rests on its ability to perform advanced spatial and/or temporal analysis on multiple layers of high resolution information. This facilitates research efforts directed at managing the global carbon cycle, mainly by providing value-added information and assisting implementation procedures. Integrated RS-GIS can act as a Decision Support System (DSS) tool in CS management and monitoring.

Integrated RS-GIS enables quantification of spatial and temporal variability of climate and soil conditions across a region (Niu and Duiker, 2006). In the long term, the deployment of RS-GIS is envisaged to exhibit cost- and time-effectiveness (Updegraff *et al*., 2005) due to its ability to delineate uncertainties (Patenaude *et al*., 2004), to improve observational accuracy (Gamon *et al*., 2004) and to allow rapid data acquisition from a wide regional coverage in a non-destructive manner (Chandra and Ghosh, 2006).

Effective use of RS is contingent on ground truthing and sampling strategies so as to capture spatial and or temporal variability at the optimum scale (Fitzgerald *et al*., 2006). RS tools such as Synthetic Aperture Radar (SAR), Light Duetection and Ranging (LiDaR) and satellite sensors such as Landsat, SPOT and Ikonos have been used to map carbon stocks (Goetz *et al*., 2009). In the Huang Hai Plain of China, soil databases were combined with weather records to create eighteen EPIC (Environmental Policy Integrated Climate) models to generate climate change predictions for agricultural cropping systems. It was found that the total soil CS potential in the area, double cropped with wheat-corn under a conventional tillage system, would range from 0.16-0.43 Pg of C without any significant impact on crop yields (Thomson *et al*., 2006). In a recent investigation to model soil CS potential in eroded areas, the relationship of soil CS potential with soil erosion type, altitude, soil type and soil parent material were explored using a GIS (Shi *et al*., 2009). This study showed that recovery of vegetation increases CS potential of eroded soils. Regional-scale GIS has been used as the operating platform in the development of C-Lock, a new system that standardizes estimation of agricultural carbon sequestration credits. This system incorporates CENTURY, a biogeochemical model that simulates carbon, nutrient and water dynamics for different types of ecosystems. Such a system facilitates precision carbon management, an emerging frontier of applied science.

Besides the agriculture sector, deployment of geo-spatial technologies for CS management has also been documented in the forestry sector. Caldwell *et al.* (2007) illustrated the complexity of Afforestation and Reforestation (A/R) programs in China using an integrated assessment approach based on RS-GIS. A/R programs are aimed at increasing CS and improving biodiversity. Their integrated assessment model comprised sub models, qualitative assessment modules, processed scenarios and final outputs for income rates Fig. 2. The A/R program gave farmers income benefits in terms of financial support for the first 8 years. However, it was predicted that in the long term when subsidies are halted farmers would experience income loss.

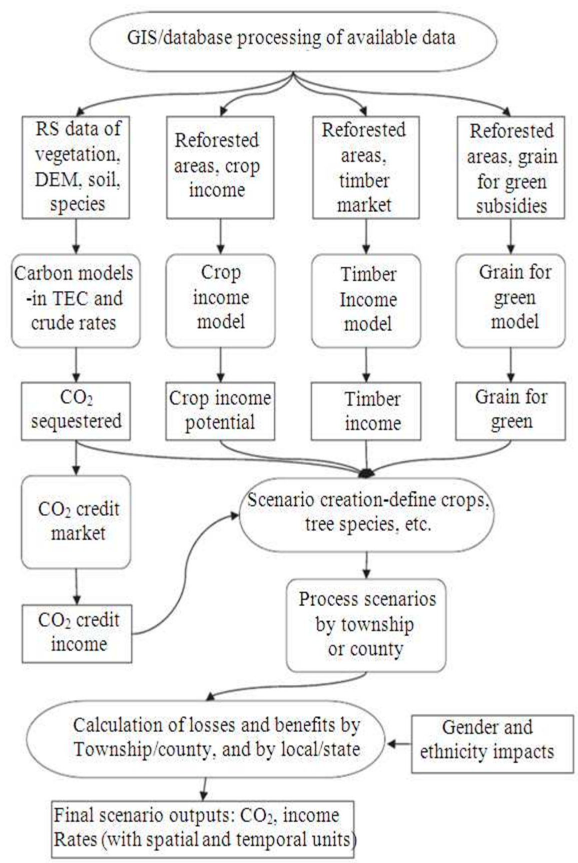

Fig. 2: An integrated assessment model based on RS-GIS (Caldwell *et al*., 2007)

In the USA, Niu and Duiker (2006) reported that Landsat imagery integrated into a GIS was used to identify hotspots (i.e., high CS capacity locations) for afforestation programs in the USA. This approach enabled the prediction of potential CS capacity as a result of afforestation for 20-50 years. Using a similar approach, it is predicted that afforestation efforts in Latin America may generate up to USD2.3 billion worth of carbon credits in the next 20 years (Benitez and Obersteiner, 2006). In Ukraine, NOAA AVHRR imagery and mathematical models were used to estimate the total amount of carbon released due to the forest fires and the subsequent loss of CS capacity (Volosko-Demkiv and Ryabokonenko, 2005).

DISCUSSION

Information about CS capacity and estimation of carbon credits in a regional scale will assist policy makers in outlining effective measures for best carbon management practices in the current and future era. There is a steady accumulation of literature on the application of RS, GIS or both in CS management of forests (Benitez and Obersteiner, 2006; Campbell *et al*., 2008; Chen *et al*., 2007; Neilson *et al*., 2007; Upadhyay *et al*., 2006), land use change (Inoue *et al*., 2010; Schaldach and Alcamo, 2006; Tornquist *et al*., 2009; Upadhyay *et al*., 2005) and croplands (McCarty *et al*., 2007; Watts *et al*., 2009). The application of RS platform such as Landsat was found to assist in classifying crops according to their CS potential by verifying and documenting crop rotations and cropping intensity (Bricklemyer *et al*., 2007). Wang *et al*., (2010) used an integrated RS-GIS approach to investigate CS potential in above and below-ground sinks of local forests in the Guizhou Province of China.

Spectrally-based Normalized Difference Vegetation Index (NDVI) and other vegetation indices, derived from RS platforms, are common indicators used to monitor biophysical conditions and vegetation cover. These indices are solely designed to optimize the spectral signatures of vegetation and to minimize the influence of soil reflectance and atmospheric attenuation (Patenaude *et al*., 2005). In Northern Kazakhstan, the NOAA satellite imagery, GIS data layers and NDVI measurements were manipulated to estimate CO_2 sequestration in cereal crop fields and grassland (Sultangazin *et al*., 2007).

The combined use of biomass models and NDVI data has simplified estimation of carbon stocks in boreal and temperate forests (Dong *et al*., 2003), Atlantic rainforests (Freitas *et al*., 2005), peat swamp forests (Gandaseca *et al*., 2009) croplands (Watts *et al*., 2009; Yan *et al*., 2007), biologic soil crusts (Burgheimer *et al*., 2006), bamboo stands (Du *et al*., 2010) and semi arid rangelands (Nosetto *et al*., 2006).

Recently, the United States Department of Energy established a nationwide network in an effort to implement appropriate strategies to promote CS in different regions across the nation (Litynski *et al*., 2008; Ruby, 2005). This study deployed GIS as a fundamental tool in managing information about CO_2 sources, feasible sequestration sites, relevant infrastructure and related factors in each region. GIS was also used as a DSS to screen potential storage formations, suitable transportation, source to sink matching and potential risk management solutions (Litynski *et al*., 2006). This effort led to the GIS-based National Carbon Sequestration Database (NatCarb) which provides a national view of the carbon capture and storage potential in the United States and Canada (Carr *et al*., 2009).

Quantification and estimation of spatially explicit services for CS potential may differ based on climate, management applications, history, ecosystem, species and the local communities. A case by case scenario will be most effective in producing reliable data using the RS-GIS integration. Currently, scientists are designing specific models to improve the precision of carbon stock estimates that changes through time (Goetz *et al*., 2009). Meanwhile, the voids in computing net primary productivity, depth distribution of biomass carbon, relationship between litter and carbon pools and below-ground (roots and microbes) sequestration (Lal, 2007) need to be strategically addressed if reporting of CS potential and trading of carbon credits are carried out based on geo-spatial technologies. Limited expertise and resources in developing countries necessitate knowledge sharing and cross-boundary collaboration in Reducing Emissions from Deforestation and Degradation (REDD) projects. In addition, cyber infrastructure that integrates computing environment and capabilities, should be enhanced. This would cost-effectively improve access to specific information, models, problem solving capacities and communication (Rich *et al*., 2008) in developing countries.

CONCLUSION

The synergistic role of RS and GIS technologies in CS management was synthesized. Numerous literature reports suggest that the integrated RS-GIS approach can aid CS management and monitoring strategies. In climate change mitigation, this approach can provide an efficient and cost-effective means of estimating above- and below-ground biomass, delineating spatial variability, predicting potential carbon stocks and revenues and outlining appropriate management strategies for localized and regional scale. In the near future, the deployment of an integrated RS-GIS approach for precision carbon management will become more visible.

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