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UPGRADING GEOGRAPHIC INFORMATION SYSTEMS TO SPATIAL DECISION SUPPORT SYSTEMS

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Abstract. A GIS is capable of identifying a set of land units meeting positional, temporal, topological and multiple on-site attribute criteria. Based on the combination of its generic analytical functionalities, a GIS can also be used to rank the alternative land units and propose the best or worst ones in terms of the non-weighted or weighted criteria. More advanced multi-criteria decision methods are however not easily incorporated in the GIS-framework so that extension with dedicated tools is required to upgrade the GIS to a full blown sDSS. In this paper we illustrate this upgrading of GIS to sDSS and we argue that when also temporal alternatives are dealt with, the DSS can be termed spatio-temporal. Three statements are made: (i) the presented rationale is challenged by phenomena of spatial and spatio-temporal interaction, (ii) important research avenues are present in order to optimize topological and off-site decision attributes in the spatial and spatio-temporal decision problems and (iii) the forestry domain is very suitable for study and application of all the mentioned issues due to the explicit spatial and temporal nature of the management issues which must be addressed.

Keywords: Multi-purpose forestry; Decision support

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1 Introduction

In forestry choices must frequently be made among alternative actions considering multiple forest performance-related criteria. Depending on the problem at hand, alternatives may be of a spatial (land units), temporal (rotation lengths) or silvicultural (tree species, forest management systems) nature. Performance criteria generally apply to quantity or quality of one or more forest ecosystem services and are often combined with cost efficiency. Examples of such services are carbon storage, bio-energy provision, wood production, biodiversity support, water harvest, nutrient cycling, erosion control and recreational value.

Since all these forest ecosystem services are highly variable among land units, rotation lengths and silvicultural practices, forestry-related problems not only deal with multiple criteria but also have a distinct spatio-temporal character. This inherent complexity leads to a clear need for support of the choices or decisions to be made by foresters (e.g., Garcia-Quijano et al., 2005; Gilliams et al., 2005a; Gilliams et al., 2005b). Though Geographic Information Systems (GIS) are designed for dealing with many aspects of spatio-temporal decision making, current GIS-technology does not have all the required capabilities expected from a full service spatio-temporal decision support system (stDSS) as needed in land management in general and forestry in particular.

The main objective of the present paper is to describe the concept of a GIS-based spatial Decision Support System. To illustrate the concept, we introduce the ForAndesT-sDSS, which was recently developed for support of afforestation planning in the southern Andes of Ecuador (Van Orshoven et al., 2009) using free and open source software (FOSS).

2 GIS for support of spatial decision making

Geographic Information Systems (GIS) allow users to ask questions about a predefined spatial and thematic portion of geographic reality and obtain meaningful

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answers (Wijffels et al., 2010). GIS may deal with themes as diverse as transport infrastructure and utilities, land use history and impacts of climate change on agricultural production. All GIS are underpinned by a dedicated collection of georeferenced data organized in geodatasets. Each geodataset is representing the considered geospatial entity class or terrain attribute selected from reality at given spatial, semantic and temporal resolutions. A collection of vertically integrated geodatasets is an example of a loosely organized geospatial database. If the data are stored and managed using an object-relational database management system (ORDBMS) like Oracle Spatial (http://www.oracle.com/technology/documentation/spatial.html) or PostgreSQL/PostGIS (Ramsey, 2007), the geospatial database is said to be tight or integrated.

The functionality of a GIS can be broadly categorized into geospatial data management (editing, transformation) on the one hand and information provision on the other hand. The information is generated by the conversion of the data the GIS holds in its database into answers to the questions users ask through a user interface. To this end, analytical functions such as proximity and neighbourhood analysis, overlay analysis, cost-distance analysis and map algebra complement the functions for viewing, querying and mapping the content of the database.

The analytical functions of GIS make them capable of spatial multi-criteria analysis (sMCA), i.e. the determination of real world entities or real world locations which meet specified positional, attribute, temporal and/or topological criteria. Positional criteria deal with absolute geographic location and geometric shape and require spatial functions (e.g., point-in-polygon identification, area calculation) to be assessed. Attribute criteria are dealt with by query and reclassification functions which use arithmetic, relational and Boolean operators. Temporal criteria relate to changes over time of location, shape and/or attributes. They are handled through attribute operations, topological overlay or map algebra. Topological criteria such as relative distance, spatial coincidence, contiguity, connectivity and entity hierarchy can be handled with proximity analysis (buffering, neighbourhood analysis), topological overlay and map algebra. sMCA uses a combination of all these functions to determine the set of entities, parts of entities or locations meeting the combination of criteria. sMCA thus defined does not provide a ranking of the members of this set, e.g., from best to worst. Moreover, it is hard to attribute differential importance to the criteria. As a result, sMCA does not sufficiently meet the requirements when decision makers are in need of a ranking of alternatives according to criteria they or their communities define and weigh.

Similar to sMCA, SAW (Simple Additive Weighting) is a multi-criteria decision method (MCDM) which is, or can easily be, implemented in most standard GIS-software since it is based on topological overlay or map algebra. In contrast to sMCA, SAW does provide a ranking of the alternative entities or locations according to the multiple selected attribute or temporal criteria. Moreover, it allows incorporating differential importance of the considered criteria. The Analytic Hierarchy Process (AHP) is an approach for ranking alternatives which is closely related to SAW, but which has a more elaborate theoretical and mathematical foundation (Saaty, 1980). AHP requires the careful assessment of a decision hierarchy consisting of at least four levels: goal, objectives, attributes or criteria with possibly subcriteria, sub-subcriteria, and alternatives. All members in each hierarchy level are weighted using approaches such as those proposed by Saaty (1980) or Malczewski (1999). Weights are then multiplicatively propagated through the hierarchy to create a weighted linear ranking of the alternatives. AHP has been integrated in a number of GIS-software packages like IDRISI (Eastman, 2003). In both the SAW- and AHP-approach, the decision attributes must be expressed on commensurate scales, which requires that the values are standardised, typically between 0 and 1. Also, route-finding algorithms are frequently implemented in GIS-software. Route finding implies the search for, and ranking of, alternative combinations of network links based on one or more criteria related to the impedance of links and/or nodes.

3 Concept of GIS-based sDSS

sMCA, SAW, AHP and route finding are multi-criteria decision methods which are commonly implemented in current GIS-technology. GIS incorporating these methods can be used for identifying and ranking spatial alternatives according to multiple criteria and weights and hence can be termed sDSS. However, other types of MCDM are not typically incorporated in GIS-software, so their implementation requires an extension of the GIS with a dedicated optimization module. Examples of such MCDM are concordance methods and interval goal programming (IGP). Concordance methods are based on pairwise comparisons of alternatives, and provide an ordinal ranking of the alternatives. When two alternatives are compared, these methods can only express that alternative A is preferred to alternative B, but cannot indicate by how much. The most well known concordance approach is the ELECTRE method (Roy, 1968) and its variants. IGP (Ignizio, 1974) is essentially an iterative database query procedure in which, in each iteration, those alternatives are selected which meet the applica-

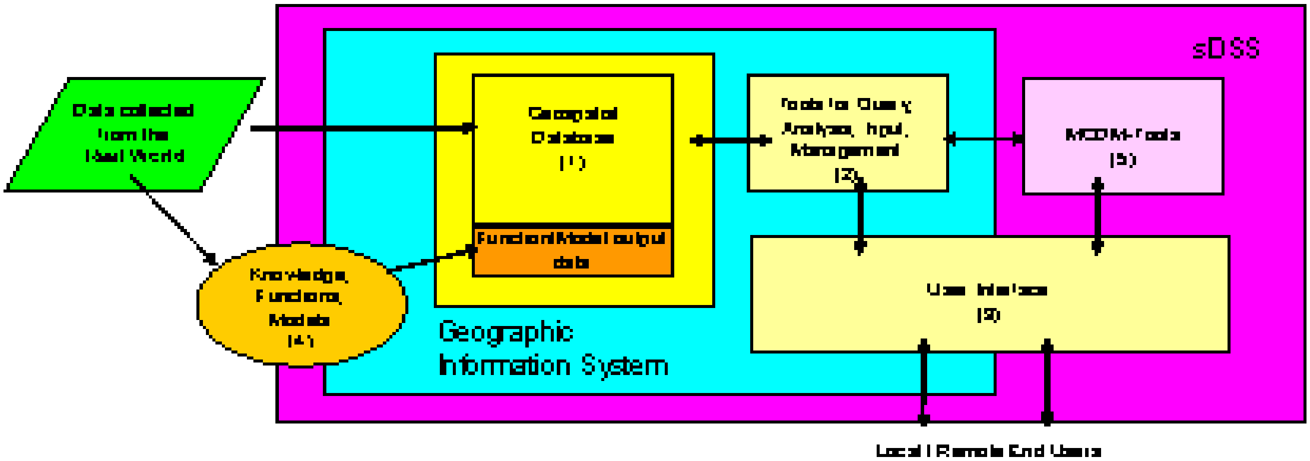

Figure 1: sDSS encompassing a GIS

ble target values. When the best alternatives are to be determined, the initial target values correspond to maximal values for benefit attributes and minimal values for cost attributes. In each iteration, the target values are adjusted downward or upward so that the probability of finding alternatives increases. Differential weighting of decision criteria is implemented by differential adjustment of the target values in each iteration. Large weights correspond to small adjustments, while larger tolerances are associated with small weights. IGP does not require standardisation of the decision attribute values.

In Figure 1, the cyan box represents a generic GIS encompassing (1) a geospatial database, (2) a toolbox for database management, query and analysis and (3) a user interface. The database is populated with data about real world entities or terrain characteristics, and with data generated through a Knowledge and Model Base (KMB, 4). The latter pertain mainly to the projected or simulated performance attributes of particular interventions on particular land units and during particular time lapses. As indicated by the purple box, the sDSS is created by extending the GIS with a MCDM-module like IGP (5).

4 The GIS-based sDSS ForAndesT

The ForAndesT is a spatial decision support system which was developed in a series of research projects on the site-specific environmental and socio-economic impacts of afforestation. Its primary objective is to make available the knowledge gained in the research, to support planners and managers of afforestation projects in two catchments in the southern Andes of Ecuador.

The decisions which ForAndesT supports deal in the first place with land units. Land units are the alternatives which must be ranked according to their suitability for afforestation with a given tree species and for a given rotation length. The suitability is dependent upon one or more of five criteria, i.e. attributes of the land units. The five decision attributes are run-off production, sediment production, carbon sequestration in soil, carbon sequestration in biomass and income generated, all cumulated over the considered rotation length. All of these are intrinsic on-site attributes, and do not exhibit spatial interaction with neighbouring land units. The first component of the sDSS is a geospatial database with the land units as objects, each described by the five decision attributes for each of two silvicultural systems (either *Eucalyptus globulus* or *Pinus patula* plantations). Land units are defined in terms of soil, climate, topographical characteristics and initial (prior to afforestation) land-use type. A land unit is represented by a set of pixels characterized by the same value for the diagnostic and consequently also for the decision attributes. The second component is a toolbox for query, visualization and analysis. The third one is a user interface. The performance attribute values of the combination of land unit, silvicultural system and rotation length were assessed by means of knowledge and statistical or mechanistic models available in the ForAndesT knowledge and model base (KMB). The KMB can be considered a fourth component which is necessary to populate the database. Finding land units of optimal return in terms of two or more performance attributes, which in addition may receive different relative importance, is hardly possible with this four-component system. Therefore, the GIS was extended with a fifth component that implements IGP. With addition of this component, the GIS can effectively function as a sDSS. Since the geospatial database encompasses data for two tree species which can be used for afforestation, and since the decision attributes are available for each land unit, each tree species and two rotation lengths (10 and 30 years), the sDSS is not only capable of ranking land units for afforestation by tree species and rotation length. It can also rank tree species by land unit and rotation length, and rotation length by tree species and land unit as well.

As a result, the user of the ForAndesT-sDSS can obtain answers to questions of the type 'What are the best land units (Where) ?', 'What is the best rotation length (How long) ?' and 'What is the best silvicultural system (How) ?'. In our opinion the 'Where' capabilities allow the qualification 'spatial' for this decision support system' while the 'How long' capabilities are too much dependent upon the temporal attributes in the database to justify the term 'spatio-temporal'.

Figures 2 and 3 display the answer provided by the ForAndesT-sDSS to the question: 'Where in the Tabacay catchment (6.652 hectares) are the 250 hectares which will deliver the best performance 30 years after conversion of the current land-use to *Eucalyptus globulus* plantation ?'. Herewith the performance is expressed in terms of two of the five possible criteria: (i) income generated (INC) and (ii) carbon sequestered in the soil (SOC). The difference between Figures 2 and 3 is that in the former the ratio of the weights for INC and SOC is 1/3 while in the latter the ratio is 3/1. Comparison of the figures shows that the selected land units are only partly coincident. In addition, the total area of the selected land units is larger than 250 hectares and not equal. Indeed, since several land units may have identical or very similar values for the INC and SOC-criteria and since in each IGP-iteration the target values are adjusted with a relatively broad interval it is likely that more than the required area is selected.

5 FOSS in the ForAndesT-sDSS

The ForAndesT-GIS is built upon a geospatial database holding the geometric data (the land units) in ASCII-raster format. The cells in the ASCII-raster are labeled according to the land unit to which they belong. This label provides the key to a set of relational tables in which all land unit characteristics and forest performance data are held. The latter are maintained and managed using a Free and Open Source Software (FOSS), i.c. PostgreSQL-ORDBMS (Ramsey, 2007). The database model is designed for easy extension to other geographic regions and other decision criteria. Another FOSS, MapWindow-GIS (Ramsey, 2007), provides the standard geospatial tools to query, visualize and process the contents of the database. The IGP-module was programmed using the general purpose C# language. Despite the fact that the sDSS is developed making exclusive use of FOSS, the majority of its intended users have the Microsoft Windows operating system, which is why Microsoft's .NET-framework is an additional software requirement for making the sDSS operational on Windows-based computers.

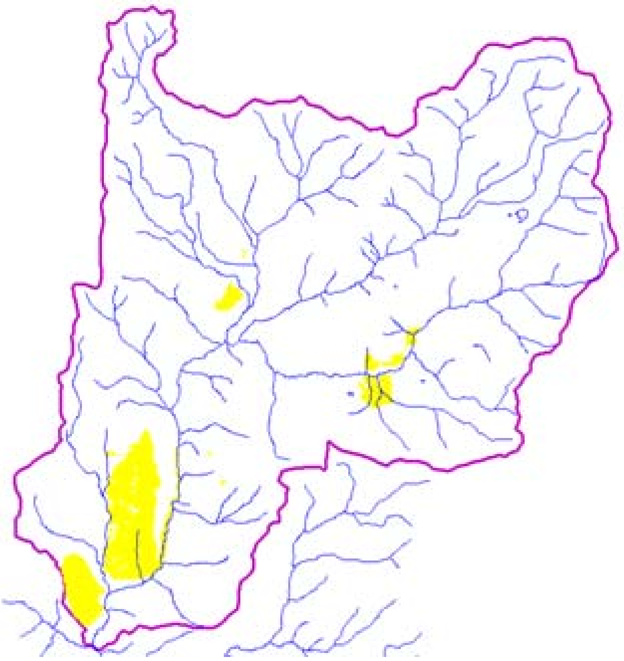

Figure 2: Land units (>=250 hectares, yelloww) selected as being the best for conversion of the initial land-use-type to *Eucalyptus globulus* plantation when the objective is to generate the maximal possible income and to store the maximal possible amount of carbon in the soil 30 years after the conversion, while the carbon stored is three times more important than income generated

6 Discussion of concept and implementation

The combination of generic GIS-functionalities, an operational KMB and a MCDM like IGP seems to provide a robust framework to support decisions related to land-use-type allocation in which multiple on-site attribute, positional and temporal criteria play a role. Topological criteria like adjacency and connectivity are however out of scope. It is not possible to find zones consisting of several contiguous polygons or cells which *together* outperform other zones. This may apply to the search for compact non-convex zones which are sufficiently large for the creation of a recreational forest and which at the same time deliver the best possible biophysical ecosystem services. The question becomes even more complex when not only on-site attribute criteria are considered (e.g. carbon stock in soil) but also off-site criteria like

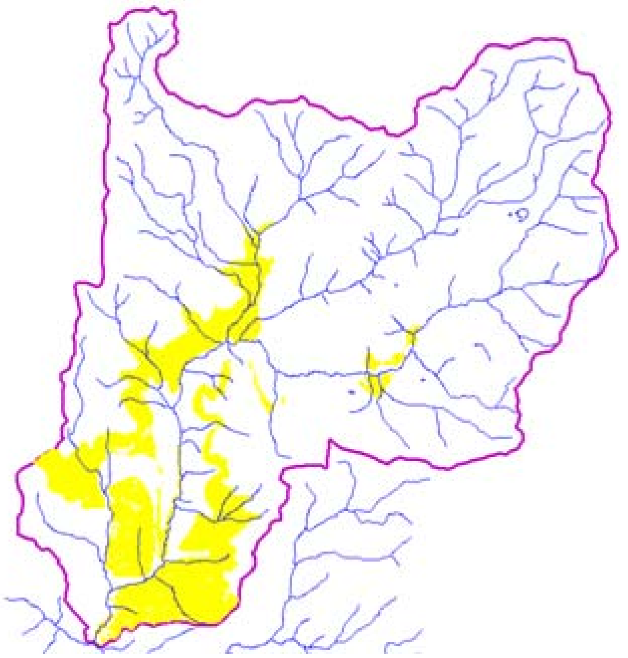

Figure 3: Land units (250 hectares) selected as being the best for conversion of the initial land-use-type to *Eucalyptus globulus* plantation when the objective is to generate the maximal possible income and to store the maximal possible amount of carbon in the soil 30 years after the conversion, while the income generated is three times more important than the carbon stored

sediment delivery in the river system draining the watershed in which an afforestation project is planned. Such off-site criteria are characterized by spatial or spatio-temporal interaction. An intervention on one location at a given time influences the performance of other locations possibly at other times. Obviously, to deal with topological criteria in the absence or presence of spatial interaction, additional tools are required. These may be part of a preprocessing step in which e.g. adjacency is used in a filter operation of eligible pixels. They may also be incorporated in the core sDSS by means of e.g., integer programming techniques (Vanegas et al., 2009a; Vanegas et al., 2009b). However heuristic methods seem to be preferable because of better computational performance even if the obtained solutions are rather near-to-optimal (Vanegas et al., 2008).

The 'Where ?' question as addressed by the ForAndesT-sDSS is limited to one land use type (LUT) at a time. In order to allocate several LUT, an order of priority must be defined. First the LUT with highest priority will be allocated within the available space. For the second and following LUT, only the remaining space is considered. In order to proceed to simultaneous allocation of several LUT without setting of priorities, a linear programming approach will be required.

7 Conclusions

In our rationale, a GIS is capable of identifying a set of land units meeting positional, temporal, topological and multiple on-site attribute criteria using relational operators like 'equal to' and 'larger than'. Based on the combination of its generic analytical functionalities (overlay, reclassification, map algebra, proximity and network analysis) in sMCA, SAW, AHP and route-finding approaches, a GIS can also be used to rank the alternative land units and propose the best or worst ones in terms of the non-weighted or weighted criteria. More advanced MCDM like IGP are however not easily incorporated in the GIS-framework, so that extension with dedicated tools is required to upgrade the GIS to a full service sDSS. When temporal alternatives also are dealt with, the DSS can be termed spatio-temporal but care should be taken not to use this term when merely temporal attributes are involved. The presented rationale is challenged by phenomena of spatial and spatio-temporal interaction and by the wish to allocate multiple land-use types simultaneously without prior judgment of their relative importance. Important research avenues are present in order to optimise topological and off-site decision attributes in the spatial and spatio-temporal decision problems. The forestry domain is very suitable for study and application of all the mentioned issues due to the explicit spatial and temporal nature of the management issues which must be addressed.

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