AFFOREST sDSS: a metamodel based spatial decision support system for afforestation of agricultural land

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Abstract. The concept and structure of the Spatial Decision Support System AFFOREST sDSS dealing with environmental performance (EP) of afforestation on agricultural land in northwestern Europe, is presented. EP is defined in terms of three environmental impact categories: (1) carbon sequestration (2) groundwater recharge and (3) nitrate leaching. The core of the sDSS is a raster based geographical database which allows for queries addressing 14 types of questions on where, how and how long to afforest in order to reach a desired EP or change in EP due to afforestation of the agricultural land. First the study area is differentiated according to the site conditions (based on soil texture, soil drainage, initial land use, yearly average precipitation, and yearly average N deposition. Then the EP for every site class is computed as a function of time using the VSAM metamodel. VSAM results from a conceptual simplification of an existing mechanistic point model, the forest process model SMART2. Input data for the metamodel are limited to the classified site conditions, the tree species used for afforestation, the afforestation strategy and the evaluation time. Besides limiting the data requirements, the metamodel approach allows for rapid and flexible computations on large numbers of pixel classes. Finally, depending on the type of question, the sDSS creates georeferenced outputs based on SQL-type spatial or attribute queries and more advanced multiple goal programming techniques.

Introduction

Afforestation of agricultural land is causing a major land use change in Europe. It is at least partly driven by the McSharry and Agenda 2000 reforms of the EU's Common Agricultural Policy (Regulation (EEC) no 2080/92).

Afforestation is defined as the direct human-induced conversion of land that not has been forested for a period of at least 50 years to forested land through planting, seeding and/or the human-induced promotion of natural seed sources (2001 Marrakesh Declaration and the Marrakesh Accords). Although it is generally assumed that afforestation may play a substantial role in meeting the obligations under the Kyoto-protocol by increased carbon sequestration in soil

and biomass (Powlson et al. 1998; Watson et al. 2000) limited scientific understanding is readily available about the influence of the former agricultural management, the site conditions and the afforestation practice. Similar uncertainty holds for other possible environmental impacts of afforestation like its effect on recharge of groundwater bodies and leaching of nitrates to these bodies (e.g. Rijtema et al. 1994; Rowe et al. 1994; Jussy et al. 2000). One of the goals of the AFFOREST project (EU 5th framework program for Research & Technological Development) is to bundle the existing information and perform extra research to strengthen the scientific understanding on the effect of afforestation for three environmental impact categories (EICs), i.e. carbon sequestration, nitrate leaching and groundwater recharge.

The existing knowledge is extended with newly gathered information and combined into a Spatial Decision Support System (sDSS). In the late seventies the first decision support systems where developed, mainly to support ill-structured management problems. Since their development decision support systems became increasingly more important in a wide variety of fields, education, agriculture, the military, health care and forestry (Eom et al. 1990).

Because decision support tools have been developed in a wide variety of domains and for use by people with different backgrounds, a clear unequivocal definition of a Decision Support System (DSS) is hard to find. According to Janssen (1992) definitions of DSS range from restrictive, e.g. interactive computer based systems that help decision-makers utilize data and models to solve unstructured problems (Gorry et al. 1971) to extremely open, e.g. any system that makes some contribution to decision making (Sprague et al. 1989).

A common feature of DSS is that they are built to provide end user's with interactive support of their decision-making processes. Hence, end user's requirements are essential in DSS development. Sprague (1980) defined three technology levels to structure the domain of DSS development:

The first technology level is a *Specific DSS*. Information system applications that allow a specific decision maker or group of them to deal with specific sets of related problems.

The second technology level is a *DSS Generator*. It is an integrated package of software that provides a set of capabilities to build a specific DSS quickly, inexpensively and easily (Turban 1995). Electronic spreadsheet packages such as Excel and integrated packages such as Microsoft Office can be considered as limited DSS generators. They provide model manipulation, model building (spreadsheet models), database management and dialogue management (menus) capabilities (O'Brian 1990).

The third technology level called *DSS Tools* is the most fundamental level of technology applied to develop a DSS and consists of software utilities and tools. These hardware and software elements facilitate the development of a Specific DSS or a DSS generator, examples include graphic editors, query systems, random number generators etc.: elements used to build both specific DSS and DSS generators (Sprague et al. 1982).

In the case of decisions to be taken with spatial implications, Geographical Information System (GIS) software can be used as a DSS Generator for the development of a specific DSS by incorporating models that make use of a spatial database and a GIS-interface. Such a DSS integrating GIS facilities is called a sDSS. sDSSs have been extensively and adequately covered in the literature (Craig et al. 1991; Densham 1991; Moon 1992; NCGIA 1992). Techniques such as dynamic data exchange (DDE), object linking (OLE) and open database connectivity (ODBC) allow data transfer from the GIS to the modeling software, providing facilities not found in the GIS, and then back to the GIS for storage and visualization. Comprehensive spatial decision support will require the effective integration of GIS and non-GIS technology. The challenge for sDSS builders is to achieve an appropriate synthesis of modeling techniques and interface with database approaches, drawn from the GIS and specialized domains. Next to this, Geographic Information Systems (GIS) technology and applications gained considerable interest in recent years. A GIS is an information system under laid by a spatially explicit database. Within the GIS-domain, there is increasing interest in the use of GIS software to provide decision support. Maguire (1991) points out that some authors have even argued that GIS is a DSS by definition. However the description of these GIS applications as being DSS is not based on the reference of DSS literature. According to Deekshatulul et al. (2000) the addition of analytical modeling capabilities and/or expert knowledge to the management system, spatial modeling tools, graphical display and tabular reporting capabilities of a GIS creates a sDSS. sDSS can therefore be seen as a particular subset of DSS, i.e. of systems meant to provide support in decisions for which locations are crucial.

In order to assess the environmental impact of the afforestation process, the environmental performance (EP) of the initial system, i.e. the agricultural land, must be compared with the EP of the same land after afforestation. With respect to AFFOREST sDSS, EP is defined in terms of the three selected EICs i.e. carbon sequestration, nitrate leaching and groundwater recharge. The magnitude of the changes in EP does not only depend on the characteristics of the land unit (latitude, available radiative energy, climate, soil, hydrology and the initial agricultural land use and management) and the time lag after which EP is evaluated. Also the afforestation practice (tree species, land preparation) used and the management (thinning, rotation length) of the afforested site, is known to be important (Winjum et al. 1992; De Wit et al. 1999; Ballard 2000).

As a result, four basic components of the modeled system are distinguished (Figure 1)

- the *initial system* characterized by the variables that are necessary to calculate EP, soil type, a given annual average precipitation amount, a given annual average atmospheric nitrogen deposition, agricultural land use. Its EP is assumed to be constant.
- the *afforestation strategy* defined by the choice of tree species, stand preparation and stand tending.
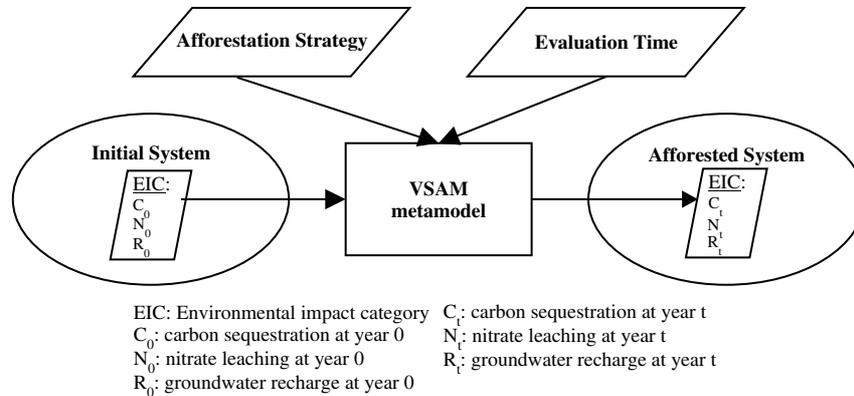
Figure 1. The structure of the AFFOREST sDSS.

- the *afforested system* characterized by the same soil type, precipitation and atmospheric deposition value as the corresponding initial system and a non-steady EP depending on the afforestation strategy.
- the *evaluation time* is the period of the changed land use since afforestation at which the change in EP between the initial and the afforested system is evaluated.

Particular decisions to be supported by AFFOREST sDSS relate to the selection of sites and the specification of afforestation practices and management with a view to optimize one or more of three EICs: carbon sequestration in the ecosystem including biomass and soil, groundwater recharge and nitrate leaching to deeper soil layers and groundwater bodies. Since these impact categories are highly dependent on spatially variable site conditions, the basic information is stored and processed in a geographical database, so the term sDSS is justified.

The envisaged users of AFFOREST sDSS are afforestation policy planners in national and regional administrations and local managers of afforestation projects. To accommodate for these two distinct categories of users, two corresponding levels of spatial resolution and semantic detail have been identified. At the more detailed project planning level, a spatial resolution of 1 ha was selected. If the input data are available or can be estimated with sufficient accuracy and precision, the integrated model can be operated at this field scale. For policy planning at the regional scale, a spatial resolution of 1 km^2 has been selected.

Heuvelink (1998) and Van Rompaey et al. (1999) showed that due to the increase of the minimal considered area, the related increase of the variability of the site conditions, negatively affects overall model performance. This in turn can justify the use of a conceptually simplified model, which requires a smaller set of input variables and operates at a reduced temporal and spatial resolution. Because, even if the model structure is correct (or at least

adequately representing current knowledge), the uncertainty in the output of complex models may still be large due to the uncertainty in the input data. Selecting the correct model for different scales is a difficult task and must be done with caution (Van Rompaey 1999). Other advantages of using a simplified model in a DSS are the calculation speed and the transparency for non-specialist end user's.

Besides a metamodel and a spatial database providing input data and storing model output, tools are needed to allow end user's to formulate particular questions and the sDSS to provide answers. An evident requirement is an intuitive interface and a powerful query builder. Most GIS-software provides query-tools of the SQL type (Din 1994). Tools to address multiple goal questions however are not included in GIS-packages and have to be added.

In this paper we describe and illustrate the concept, structure and output of AFFOREST sDSS with emphasis on the role of the metamodel and the DSS module.

Components of the AFFOREST-sDSS

The AFFOREST sDSS is implemented in the Spatial Analyst extension of ArcView® GIS 3.2 (Environmental Systems Research Institute, Redlands, CA). The standard version of ArcView® GIS 3.2 is adapted by means of its programming language Avenue. The system consists of three different modules (a metamodel, a spatial database and a decision module) and the graphical user interface (GUI). The modules are independent but commuicate via Avenue. To describe this type of interrelationship, the 'counter concept' is introduced, comparable to a client–server relationship. The decision module can be regarded as the client of the GIS-module, possibly extended with the metamodel to allow for run-time simulations. This modular approach enables the modules to be designed and function independently. It is also suited for serving different types of end user's.

The GUI is a set of newly developed dialog windows that guide end users through the system and helps them to structure their afforestation question into one of the fourteen type questions the system can handle. According to the type of question the result can either be maps, tables or both.

Figure 2 shows the main components of the sDSS and their interrelationships. The raw data and the complex process model are not integrated in the system.

The study area is represented by an ArcView grid. Each pixel class of this grid is used as input. The classified site conditions define a categorical raster, the characteristics of each cell, its EP under agriculture and its EP from year 1 to 100 years of afforestation using a specified afforestation practice, are all stored in output tables precalculated with the metamodel and linked to the categorical raster grids.
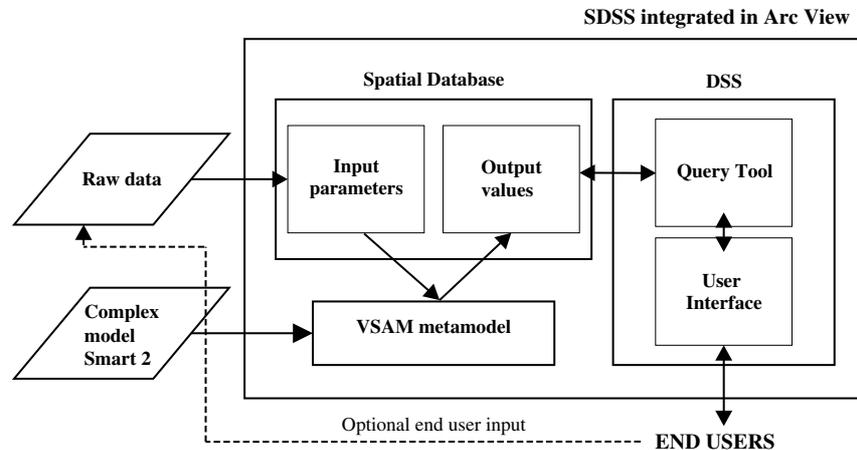
SDSS integrated in Arc View

Figure 2. Schematic representation of the modeling process.

These input parameters are derived from 'raw' data of soil and land use maps, georeferenced sets of data on precipitation and atmospheric deposition (Figure 2). Since AFFOREST sDSS covers several regions and countries, available raw data need to be harmonized regarding the resolution, spatial reference system and regarding the semantics of the data before it can be implemented in the system. Transfer rules and functions (Bouma and Van Lanen 1987; Van Ranst et al. 1995) need to be applied on the harmonized data in order to obtain the model input classes. Texture classes from national soil maps can first be harmonized to FAO texture classes (FAO 1970) and then translated into the soil classes supported by the sDSS, using one transfer function or rule. It is also possible to translate each local texture classification into the input variable using a specific transfer function, rule or procedure first and to harmonize afterwards (Van Orshoven et al. 1999). This procedure is not included in the system as such, but a description of the work is given in the help files, so that end users can transform their own data into the desired format for the system.

Based on the categorized data, the Very Small Afforestation Model (VSAM) derives parameters via lookup tables (Kros et al. 2000) e.g. for the soil input data a C/N ration is found in the lookup tables. VSAM then calculates time series of EP for each pixel class and afforestation practice. The output is stored in the database where it is available to the DSS module. The presence of metamodelling capacity in the sDSS is particularly important to limit data requirements and when the model output is not stored as such in the GIS system, which is the case in our system, but rather when new basic data is introduced or when output is computed in real time upon querying.

Finally, the DSS module transforms end user questions into type questions (queries) comprehensible to the system, activates the appropriate optimization sequence and delivers the output in a variety of ways.

Metamodel

The model VSAM used in the sDSS is further termed the metamodel. Basically, a metamodel is a model of models (Kleijen 1987). The objective of a metamodel is a simpler expression of the underlying model. Hence metamodelling can be considered as an abstraction technique that changes the form of a model (Frantz 1995). This abstraction can be done statistically (e.g. Urban et al. 1999) but other ways are possible using a phenomenology-rich theoretical approach or some other form of synthesis (Kerhervé et al. 1997; Geisler et al. 1998; Belaunde 2001; Davis 2001). According to Kleijen et al. (2000) metamodels can have four general goals: problem entity understanding, prediction, optimization and aiding in the verification and validation of the model simulation. For the present exercise, the metamodel VSAM is used for prediction. It is not based on a statistical approach but on an ad hoc simplification of an existing dynamic process oriented model. It is conceptually derived from the process-based model SMART2 (Kros et al. 2002). It simulates processes in the soil solution as well as in the solid phase. The model consists of a set of mass balance equations, describing the soil input–output relationships and the rate-limited and equilibrium soil processes. Soil characteristics that are simulated are the changes in soil solution concentrations and solute fluxes. The net element input from the atmosphere, as the product of deposition and filtering factor, seepage, geochemical interactions in the soil, and a complete nutrient cycle are influencing the soil solution and leaching. For the derivation of VSAM the following simplifications were performed: (i) VSAM is limited to N related processes, all other geochemical processes were skipped (ii) there is no feed-back of pH on the mineralization rate (iii) the time step is one year instead of one day and (iv) the climate (precipitation, temperature) is assumed not to vary over the years. As shown by Kros (2002), nitrogen and carbon cycling and nitrogen leaching in semi-natural terrestrial ecosystems can be modeled adequately by using a yearly time step.

These simplifications yield a model which uses simple equations that directly generate the EP in terms of carbon, water and nitrogen balances as a function of location (climate, soil, land use, deposition level) of the initial agricultural system on the one hand and of the afforested land system (taking into account the tree species choice, in the present version stand preparation and stand tending are not yet taken into account by VSAM) at different time lags from the start of the afforestation on the other hand (Figure 1).

VSAM consists of four sub models computing: (1) carbon sequestration in biomass, (2) carbon sequestration in soil, (3) water infiltration and (4) nitrate losses to deeper soil layers and groundwater. The top boundary of the model is the vegetation canopy whereas the bottom boundary is the bottom of the root zone. Contrary to SMART2, that is limited to semi-natural ecosystems, VSAM is completed with simplified agricultural processes.

The initial agricultural system is considered to be in a steady state for the studied impact categories: carbon sequestration is assumed to be zero, nitrate

leaching and groundwater recharge under agriculture are assumed to be constant over the years. Carbon sequestration in agricultural systems is assumed to be zero because it is highly uncertain whether arable land sequester carbon or not. For Europe as whole estimates ranges from -300 for crop land to 100 Tg C/y for grassland (Janssens et al. 2003). This is of course not the case for the newly planted forests

Basic equations used in the VSAM metamodel are: For carbon sequestration (C_{seq})

$$C_{seq\ tot} = C_{seq\ tree} + C_{seq\ soil} \tag{1}$$

where $C_{seq\ tot}$ is the total sequestered carbon (kg ha^{-1} yr^{-1}), $C_{seq\ tree}$, the carbon sequestered in living tree biomass (kg ha^{-1} yr^{-1}), and $C_{seq\ soil}$: carbon sequestered in soil by litter accumulation (kg ha^{-1} yr^{-1}). Carbon sequestered in living tree biomass is calculated with a logistic growth function, whereas carbon sequestration in the soil is calculated from litter input followed by a first order decay (Kros 2002).

Nitrate leaching is calculated as the difference between the nitrogen input through atmospheric deposition and the nitrogen sequestration or loss through net uptake, immobilization and denitrification:

$$N_{le} = N_{in} - N_{gu} - N_{im} - N_{de} \tag{2}$$

where N_{le} is the total amount of nitrate leached in kg ha^{-1} yr^{-1}, N_{in}, the nitrogen deposition in kg ha^{-1} yr^{-1}, N_{gu}, the nitrate growth uptake in kg ha^{-1} yr^{-1}, N_{im}, the nitrogen immobilization in kg ha^{-1} yr^{-1}, N_{de} the denitrification in kg ha^{-1} yr^{-1}. Nitrogen uptake is directly linked with tree growth by the C/N of the stem,

$$N_{gu} = C_{seqtree} * CN_{tree} \tag{3}$$

where CN_{tree} is the Carbon to Nitrogen ratio in a tree. Nitrogen immobilization is directly linked with the C_{seq} of the soil by the C/N of the soil organic matter:

$$N_{im} = C_{seqsoil} * CN_{soil} \tag{4}$$

where CN_{soil} is the Carbon to Nitrogen ratio in the soil. The CN_{tree} remains constant during the simulation period (dependent on tree type), whereas the CN_{soil} is variable through a reduction function that denpends on the CN_{soil} (Kros 2002).

For groundwater recharge

$$R = (P - \text{rfLAI}(t) * (E_i + E_{tr})) * (1 - f_{ro}) \tag{5}$$

where R is the recharge in m yr^{-1}, P, the precipitation in m yr^{-1}, and rfLAI(t), the reduction function for Leaf Area Index (LAI), calculated as the ratio between the actual leaf biomass and the maximum leaf biomass. E_i is the interception m yr^{-1}, E_{tr}: evapotranspiration m yr^{-1}, and f_{ro}: the runoff
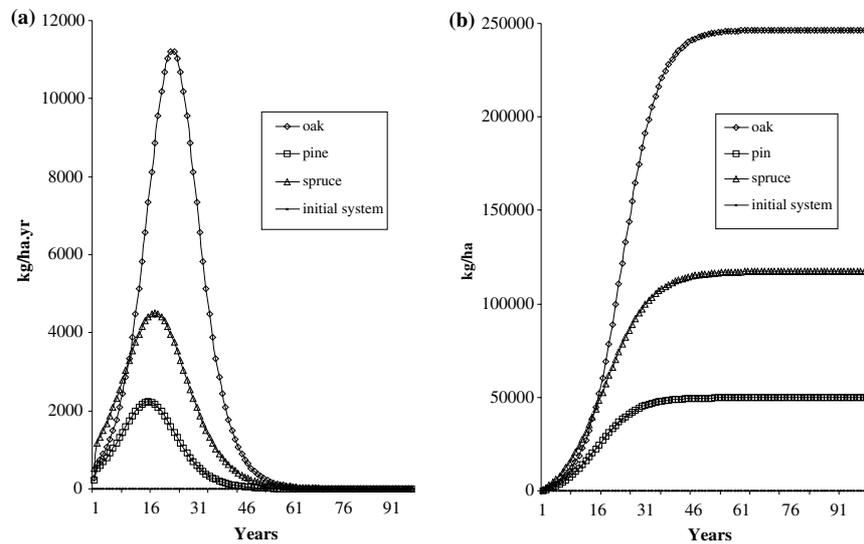
Figure 3. VSAM model output: Carbon sequestration as a function of time after afforestation with different tree species on a moist clay soil with 0.83 m yr^{-1} precipitation and 25 kg ha^{-1} yr^{-1} nitrogen deposition. (a) carbon sequestration rate (b) cumulative carbon storage since afforestation.

fraction. A more detailed explanation of VSAM, its equations and its application procedure can be found in Kros et al. (2000 and 2003).

Figures 2–4 show the EP calculated with VSAM of an initial system (arable land on a moist clay soil with an average nitrogen deposition of 25 kg ha^{-1} yr^{-1} and an average precipitation of 0.83 m yr^{-1}) afforested with three afforestation strategies oak (*Quercus robur L.*), pine trees (*Pinus Sylvestris L.*) and spruce (*Picea abies L.*).) leading to three different afforested systems.

Spatial database of metamodel output

The presented metamodel is able to compute the current EP of initial system and afforested systems, for a series of afforestation strategies and time lags. EP the initial system and the afforested system and their difference are calculated, they can either be yearly or cumulative.

A database containing the calculated EP of the initial system and the afforested system can be queried using one to three of the system components defined in Figure 1 as specifiers. Table 1 presents the structure of the database.

The table in the database is connected to the value-attributed table of the grid data layers in a $n-1$ relationship that allows for spatial queries and display.

Figure 4. VSAM model output: Groundwater recharge as a function of time after afforestation with different tree species on a moist clay soil, with 0.83 m yr^{-1} and 25 kg ha^{-1} yr^{-1} nitrogen deposition. (a) groundwater recharge rate (b) cumulative groundwater recharge since afforestation.

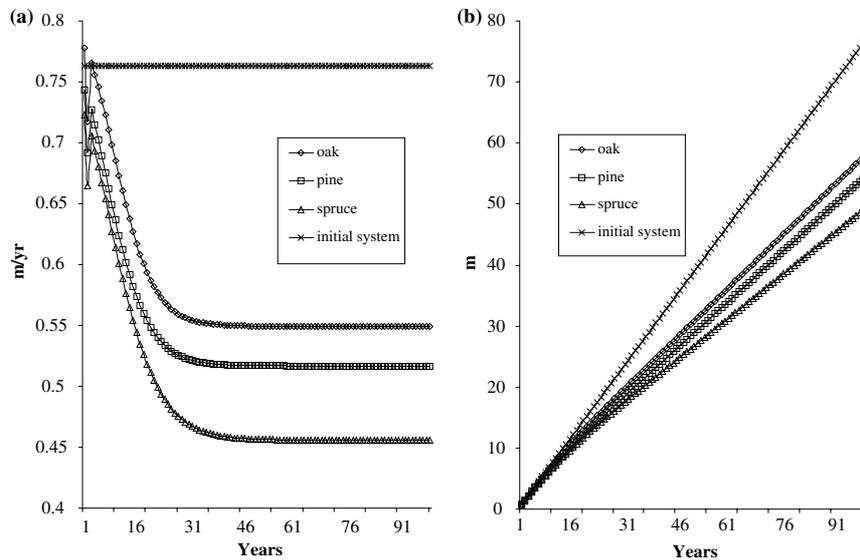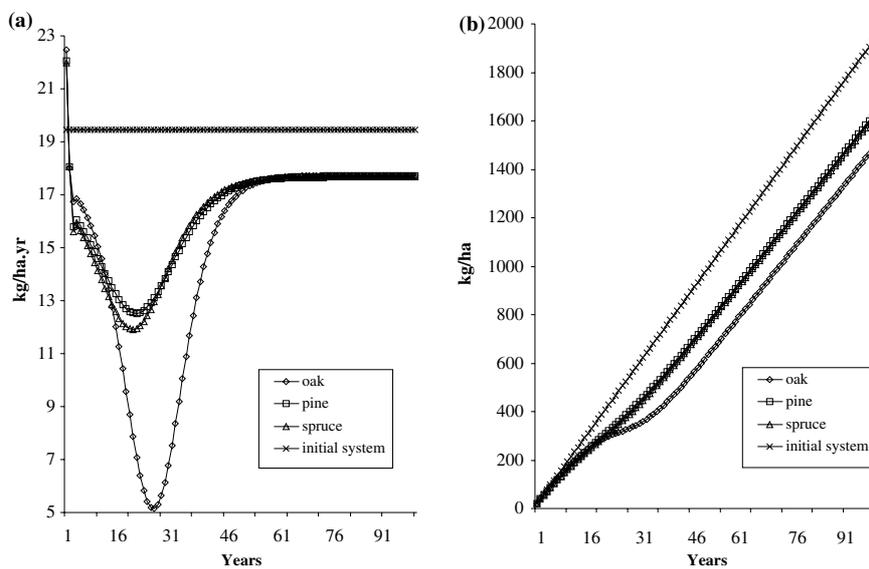*Figure 5.* VSAM model output: Nitrate leaching as a function of time after afforestation with different tree species on a moist clay soil, with 0.83 m yr^{-1} precipitation and 25 kg ha^{-1} yr^{-1} nitrogen deposition. (a) nitrate leaching rate (b) cumulative nitrate leaching since afforestation.

Table 1. Structure of the output table

Initial system characteristics (site conditions)					Afforestion strategy	Environmental performance as a function of time											
Pixel class	Prec	Soil	Ndep	ILU	Tree species	C_{t0}	C_{t1}	C_{t2}	C_{tn}	N_{t0}	N_{t1}	N_{t2}	N_{tn}	R_{t0}	R_{t1}	R_{t2}	R_{tn}
1	1	1	1	1	1	X_{10}	X_{11}	X_{12}	X_{1n}	Y_{10}	Y_{11}	Y_{12}	Y_{1n}	Z_{10}	Z_{11}	Z_{12}	Z_{1n}
1	1	1	1	2	1	X_{20}	X_{21}	X_{22}	X_{2n}	Y_{20}	Y_{21}	Y_{22}	Y_{2n}	Z_{20}	Z_{21}	Z_{22}	Z_{2n}
1	1	1	1	1	2	X_{30}	X_{31}	X_{32}	X_{3n}	Y_{30}	Y_{31}	Y_{32}	Y_{3n}	Z_{30}	Z_{31}	Z_{32}	Z_{3n}
1	1	1	1	2	2	X_{40}	X_{41}	X_{42}	X_{4n}	Y_{40}	Y_{41}	Y_{42}	Y_{4n}	Z_{40}	Z_{41}	Z_{42}	Z_{4n}
2	1	1	2	4	1	X_{50}	X_{51}	X_{52}	X_{5n}	Y_{50}	Y_{51}	Y_{52}	Y_{5n}	Z_{50}	Z_{51}	Z_{52}	Z_{5n}
2	1	1	2	4	2	X_{60}	X_{61}	X_{62}	X_{6n}	Y_{60}	Y_{61}	Y_{62}	Y_{6n}	Z_{60}	Z_{61}	Z_{62}	Z_{6n}
2	1	1	2	4	3	X_{70}	X_{71}	X_{72}	X_{7n}	Y_{70}	Y_{71}	Y_{72}	Y_{7n}	Z_{70}	Z_{71}	Z_{72}	Z_{7n}
2	1	1	3	4	2	X_{80}	X_{81}	X_{82}	X_{8n}	Y_{80}	Y_{81}	Y_{82}	Y_{8n}	Z_{80}	Z_{81}	Z_{82}	Z_{8n}

Prec = precipitation class number of a pixel.
Soil = the combined soil texture soil wetness class number of a pixel.
Ndep = the nitrogen deposition class number of a pixel.
ILU = initial land use class number of a pixel.
C_0 = Carbon sequestration of the initial system.
C_n = Carbon sequestration of the afforested system in the nth year after afforestation.
N_0 = Nitrogen leaching of the initial system.
N_n = Nitrogen leaching of the afforested system in the nth year after afforestation.
R_0 = Recharge of the initial system.
R_n = Recharge of the afforested in the nth year after afforestation.

The sDSS module

The first task of the sDSS module is converting end user's questions into database queries. Dialog windows, in which users not only need to define the system input and the output specifications (see Table 2) but also the spatial resolution and the EICs of interest, perform this task. A typical end user question could be, 'After how many years will a given initial system, afforested using a specified practice, result in a specified change in EP?' This is a type 11 question (query) (see Table 2) and produces a unique solution. The type 5 question however, formulated as 'Which afforestation practice is required for how many years in order to reach a specified EP on a specific initial system, may produce a series of solutions combining tree species and time lag matching the required target.

The theoretical type 1 question is rephrased in more practical query via the dialog windows, where the initial system is the specifier of the query while the afforested system, afforestation strategy and time are the unknown results, e.g. How does carbon sequestration change over time when afforesting arable land on a sandy soil with 0.8 m precipitation and 25 kg ha^{-1} yr^{-1} N deposition? The output of this question is a carbon sequestration curve as a function of time for all possible afforestation strategies. When information of the other two EICs is needed more curves are created.

When this question is made more specific, e.g. what is the maximal change in EP for carbon sequestration after afforestation of arable land on sandy soil

Table 2. Overview of all query types possible in AFFOREST sDSS

Question type #	Specified input	Output
1	• Initial system	• Afforested system/EP • Afforestation strategy • Time
2	• Afforested system/EP	• Initial system • Afforestation strategy • Time
3	• Afforestation strategy	• Initialsystem • Afforested system/EP • Time
4	• Time	• Initial system • Afforested system/EP • Afforestation strategy
5	• Initial system • Afforested system/EP	• Afforestation strategy • Time
6	• Initial system • Afforestation strategy	• Afforested system/EP • Time
7	• Afforested system/EP • Afforestation strategy	• Initial system • Time
8	• Initial system • Time	• Afforested system/EP • Afforestation strategy
9	• Afforested system/EP • Time	• Initial system • Afforestation strategy
10	• Afforestation strategy • Time	• Initial system • Afforested system
11	• Initial system • Afforested system/EP • Afforestation strategy	• Time
12	• Initial system • Afforested system/EP • Time	• Afforestation strategy
13	• Initial system • Afforestation strategy • Time	• Afforested system/EP
14	• Afforested system/EP • Afforestation strategy • Time	• Initial system

with 0.8 m precipitation and 25 kg ha^{-1} yr^{-1} N deposition? The output is one carbon sequestration value at a certain time step for a certain afforestation strategy.

But when simultaneous conditions are set for more than one EIC obtaining the answer becomes more complicated. It is possible that the minimal nitrate leaching values for the same pixel class is reached with a different afforestation strategy and at a different time step. This kind of solution is not useful in practice because the afforestation strategy and the time step do not coincide. Therefore more sophisticated query techniques are needed. Instead of querying the tables and selecting the maximal or minimal value for a certain EIC, the

system now has to consider which sub optimal value to select if the optimal solution does not exist. The involvement of multiple objective queries is further used to distinguish between simple and complex queries.

Simple queries
There are two types of simple queries. The first is when only one of the EIC is of interest to the end user, the querying of the output table is rather straightforward (e.g. what is the amount of carbon sequestered after 30 years for afforestation with Pine on dry sandy soils in Flanders, Belgium?). To answer this question only one column of the output table needs to be checked and the corresponding values selected. This can easily be done with standard query language (SQL) incorporated in almost any GIS software package. The answer will not be a single value, because the values for C sequestration after 30 years on that soil for Flanders must be given for all possible afforestation strategies.

The second is when the end user is interested in specific values or boundary conditions of one or more EICs (e.g. C sequestration > 5 ton ha^{-1} yr^{-1}, H$_2$O recharge between 20 and 50 mm yr^{-1} and N leaching < 20 kg ha^{-1} yr^{-1}). In this case several columns need to be verified independently to select the records complying with all conditions, standard GIS functionalities can still perform this task.

Complex queries
These are questions for which environmental parameters need combined evaluations. 'Which initial system yields the highest C sequestration and the lowest nitrate leaching in the 20th year after afforestation with deciduous trees?'

In the AFFOREST sDSS a Goal Programming technique is included for this type of question. Charnes et al. (1961) introduced goal programming (GP) as a simple linear technique. Since then a number of methodological extensions to the goal programming model have been developed such as: weighted GP, GP with intervals, fuzzy GP, etc. Here the GP with interval techniques introduced by Charnes et al. (1972) and Ignizio (1974) is used. If the maximum C value for carbon sequestration and the minimum N value for nitrate leaching are in the same row of the table, containing data for one afforestation strategy and one pixel class, the optimal solution is found and no further querying is needed. But when the maximum and the minimum do not coincide a sub optimal solution needs to be pursued. This is done by assuming tolerance intervals around the maximum or the minimum of each EIC separately, the size of the interval is depending on the weight end users set for the EICs, if in a first step no sub optimal solutions is found the intervals are enlarged according to the weights. As soon as a common row is found the sub optimal solution is found (see Table 3). If more rows are selected, several solutions match the query. The difference between the sub optimal solutions found for each category and the maximum or minimum of that EIC can be assessed.

Table 3. Example of the database table explaining the interval selection around maximum and minimum of the two EIC after 2 years

Initial system characteristics (site conditions)					Afforestion Strategy	EP as a function of time							
Pixel class	Prec	Soil	Ndep	ILU	Tree species	Ct0	...	Ct20	...	Nt0	...	Nt20	...
1	1	1	1	1	1	0	...	14012	...	Y10	...	7.9	...
2	1	1	2	2	1	0	...	13011	...	Y20	...	5.0	...
3	1	1	3	3	1	0	...	8870	...	Y30	...	10.9	...
4	1	1	4	4	1	0	...	8736	...	Y40	...	4.6	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...

Multiple goal programming.
When max C and min N do not coincide in the same row (as is the case) there is no optimal solution. The sub optimal solution is searched by means of confidence intervals around max and min, if these intervals have coinciding rows the sub optimal solution is found.
Legend see Table 1.

This can either be relative (e.g. the sub optimal solutions lies within a 5% interval of the maximum for the environmental parameters) or it can be absolute (e.g. the difference between the sub optimal solution and the maximum for carbon sequestration is 5 ton/ha).

Case study

The performance of the described sDSS is shown in the light of calculations made for the region of Flanders (Belgium) at a spatial resolution of 1 km^2. First the raw data for Flanders have been converted to input classes for the metamodel VSAM via transfer functions for soil, land use and climate. EP of all 3780 (18 soil classes * 10 land use classes * 3 precipitation classes * 7 N deposition classes) possible initial system classes have been modeled for 100 years and every afforestation strategy, resulting in a georeferenced output table for Flanders.

This output-table formed the basis for addressing four example questions by means of the sDSS.

Questions

1. What is the amount of total carbon sequestered on former arable land located on a rich sandy soil, in the 20th years of afforestation with pine?
2. Where are the best results reached with afforestation with oak in the 30th year in terms of biggest difference in C sequestration and N leaching between the afforested system and the initial system?
3. How long does it take to sequester 40,000 kg.ha^{-1} carbon when afforesting former pastures on loess soils, with N deposition of 25 kg ha^{-1} yr^{-1} and precipitation of 0.72 m yr^{-1} using oak?

4. What is the best strategy and duration to afforest agricultural land on poor moist sandy soil, with 35 kg ha^{-1} yr^{-1} N deposition and 0.83 mm yr^{-1}? From an environmental point of view the best afforestation strategy is the one with the maximal C sequestration, groundwater recharge and N leaching.

Question 1 is a type 10 question (Table 2): Time and Afforestation strategy are input for the system and the output is the initial system and the EP. Initial system is an output because it was not completely defined in the question. Only one EIC is of interest. The result is part of the output table and is presented as such.

Question 2 is also a type10 question (Table 2): In this case a complex query is needed to answer this question. Because it is a 'where' question the output is a map (see Figure 6). Additional information on the initial system and the exact values for carbon and nitrate of these selected pixels can also be given by means of an output table.

In question 3, the afforested system, the afforestation strategy and the initial system are defined so this is a type 11 question (Table 2). This question can be solved with a simple query.

The fourth and last example question is a class 1 question type (Table 2), using initial system as input and the others as output. To answer this a complex query is needed because different EIC need to be compared to each other.
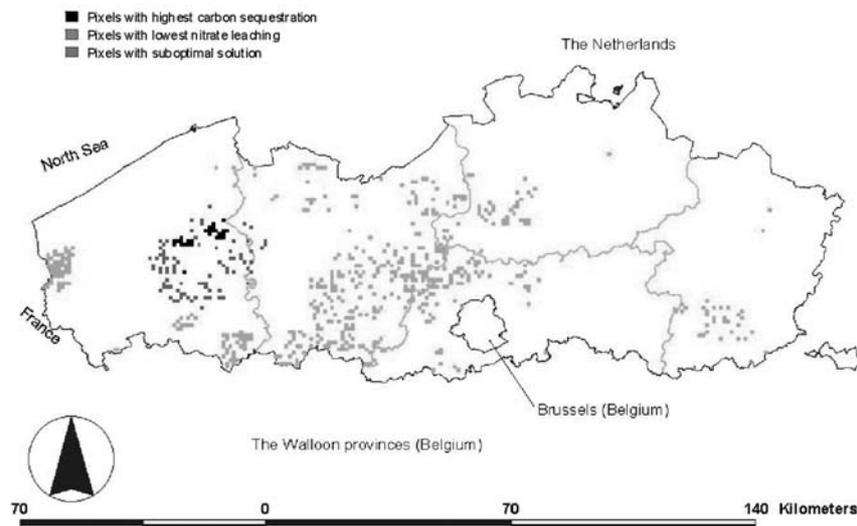

Figure 6. Location of the pixels with the: highest carbon sequestration, lowest nitrate leaching and the sub optimal solution after 30 years for Flanders when afforesting with deciduous trees.

Answers and discussion

The result for question 1 is given by Table 4. The results for carbon seques-tration varied between 4.8 and 5.4 ton ha^{-1}.yr^{-1} in the 20th year, depending on the initial land use, soil wetness, precipitation and N deposition. The lowest C sequestration is reached on a wet site with 0.83 m yr^{-1} precipitation and 25 kg ha^{-1} yr^{-1} N deposition. The highest C sequestration is reached on a moist soil, 0.81 m yr^{-1} precipitation and 75 kg ha^{-1} yr^{-1} N deposition.

The answer to question 2 is a map (Figure 6). Figure 6 shows the pixels that have the best EP for carbon and nitrate respectively. There are no overlapping pixels, what means that there is no optimal solution (no pixels with maximum C sequestration and minimum N leaching). Therefore the system has to look for a sub optimal solution, also given in Figure 6.

Further refinement is possible by using additional spatial criteria to limit the set of pixels matching the criteria, e.g. land ownership, destination of the land in regional plans, etc. Additional information such as description of the initial system or the exact values for carbon and nitrate of the selected pixels can also be given by means of an output table. The maximal carbon sequestration in this case is 14315 kg ha^{-1} yr^{-1} and the maximal decrease in nitrate leaching is -12 kg ha^{-1} yr^{-1}. For the sub optimal solution the values are: 14,300 kg ha^{-1} yr^{-1} for carbon and -7 kg ha^{-1} yr^{-1} for nitrate. The negative value for nitrate leaching expresses a nutrient shortage (trees can take up more nitrate for their growth than is available in the system) at this time step.

Table 4. Part of AFFOREST sDSS output table

Value	Count	Soil_class	Lucl	Ndep (kg/ha yr)	Precip (mm/yr)2	Cseq (kg/ha yr)
17012	6	MOISTSR	ARA	75	0.8166	5471
16012	7	MOISTSR	ARA	65	0.8166	5341
15012	14	MOISTSR	ARA	55	0.8166	5212
13012	18	MOISTSR	ARA	55	0.8303	5211
13028	9	WETSR	ARA	55	0.8303	5205
10012	26	MOISTSR	ARA	45	0.8303	5082
12012	13	MOISTSR	ARA	45	0.8166	5082
10028	9	WETSR	ARA	45	0.8303	5075
8012	2	MOISTSR	ARA	35	0.7203	4955
9012	9	MOISTSR	ARA	35	0.8166	4953
7012	27	MOISTSR	ARA	35	0.8303	4952
7028	11	WETSR	ARA	35	0.8303	4946
1012	29	MOISTSR	ARA	25	0.8303	4823
3012	8	MOISTSR	ARA	25	0.8166	4823
3028	1	WETSR	ARA	25	0.8166	4817
1028	4	WETSR	ARA	25	0.8303	4816

Value = pointer to connect with georeferenced database.
Count = amount of pixels of a certain pixel class.
Soil_class = code for the combination of texture class and wetness class.
Lucl = code for land use.

For question 3, the answer is displayed in Figure 7. After 14 years the amount of 40,000 kg.ha^{-1} is reached. Muys et al. (2002) calculated carbon sequestered in newly planted forests (mixture of oak and beech) for Belgium using the SECRETS model (Sampson et al. 1999). Their results are 45,000 kg.ha^{-1} after 10 years. The relative lower values of VSAM can be explained by different growth rates between oak and beech (Schober 1975) VSAM only used oak as deciduous tree species and in the SECRETS model a mixture of beech and oak was used to calculate growth.

For question 4, the result is that in the 25th year afforestation with oak trees, the highest annual C sequestration (16,900 kg ha^{-1} yr^{-1}), lowest annual N leaching (-14 kg ha^{-1} yr^{-1}) and highest annual groundwater recharge (0.556 m yr^{-1}). Again (see question 2) the negative value for N leaching means that there is a nutrient shortage. These results do not differ much from the results calculated by Muys et al. (2002), using the SECRETS model (Sampson et al. 1999). They found the amount of carbon sequestered in the 20th year to be 16,200 kg ha^{-1} yr^{-1} and the recharge calculated with the SWAT model (Neitsch et al. 2001) to be 0.23 m yr^{-1}. Nitrate leaching was not calculated in this report.

Although questions where limited to the Flanders region, the input data for the other AFFOREST countries (The Netherlands, Sweden and Denmark) are included in the system. If end users want to use the system to calculate EP or perform queries for other countries, they need to transform their spatial data into input parameters. A description of this procedure can be found in the help
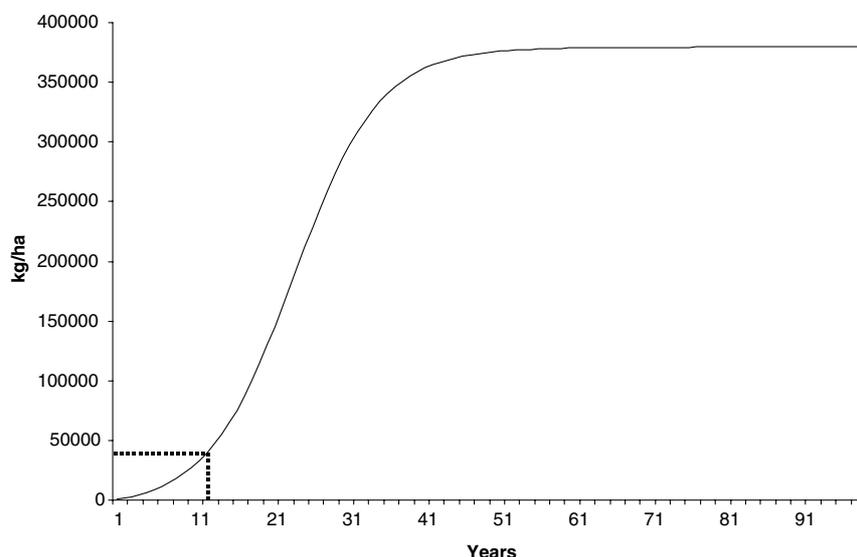

Figure 7. Cumulative carbon sequestration of deciduous trees on former arable land on loess soils with Ndep of 25 kg ha^{-1} yr^{-1} and a precipitation of 720 mm yr^{-1}.

files of the system. When the input data is stored in the AFFOREST database the EP can be calculated and specific queries for the new country can be solved.

For the moment the integrated metamodel is only calibrated for conditions in the Netherlands while validation has not been carried out in a systematic way. The quantitative results are preliminary and need further investigation. In particular, the metamodel can be improved and refined (e.g. incorporate the response to stand preparation and stand tending). However model complexity should remain in equilibrium with the input data quality. Calibration (adaptation of the lookup tables) must be done for all the regions of north-western Europe and input datasets for which it is used and validation should be explicitly undertaken using the output of detailed modeling studies and collected field data.

Conclusions and prospects

AFFOREST sDSS succeeds in answering various types of questions concerning multiple aspects of EP following afforestation of agricultural land. Hence it can be used to support related decisions on where, how and how long to afforest.

The AFFOREST system is limited to the three EICs considered at this stage but thanks to the conceptual structure it can be extended with other environmental and socio-economic impact categories after integration of a new metamodel and new input parameters. The approach described in this paper can also be used for other decision problems dealing with spatial data.

Acknowledgements

References

Ballard T.M. 2000. Impacts of forest management on northern forest soils. Forest Ecol. Manage. 133: 37–42.

Belaunde M. 2001. A stand alone metamodel for expressing model relationships. In: The OMG Technical Meeting Proceedings, April 23 2001. Paris, France, pp. 82–86.

Bouma J. and Van Lanen J.A.J. 1987. Transfer functions and threshold values: from soil characteristics to land qualities. In: Beek K.J., Burrough P.A. and McCormack D.E. (eds), International Workshop on Quantified Land Evaluation. Proceedings of a Workshop. ISSS and SSSA, Washington, DC.27 Apr.–2 May 1986, 106–110.

Charnes A. and Collomb B. 1972. Optimal economic stabilization policy: linear goal-interval programming models. Socio-Econ. Plan. Sci. 6: 431–435.

Charnes A. and Cooper W.W. 1961. Management Models and Industrial Applications of Linear Programming. Wiley, New York.

Craig W.J. and Moyer D.D. 1991. Progress on the Research Agenda: URISA '90. URISA J. 3: 190–196.

Davis P.K. 2001. Meta models to aid planning of intelligent Machines. In: PerMIS Workshop Proceedings, Sept 4. Mexico City, Mexico.

Deekshatulu B.L., Krishnan R. and Jacob Novaline N.D. 2000. Spatial Analysis and Modelling Techniques - A Review. http://pages.hotbot.com/edu/geoinformatics/f138.html.

Densham P.J. 1991. Spatial Decision Support Systems. In: Maguire D.J., Goodchild M.F. and Rhind D.W. (eds), Geographical Information Systems: Principles and Applications, vol. 1. Langman, London, pp. 403–412.

De Wit H.A. and Kvindesland S. 1999. Carbon stocks in Norwegian forest soils and effect of forest management on carbon storage. Rapport fra skogforskningen – supplement 14, Norsk institut for skogforskning (NISK).

Din A.I. 1994. Structured Query Language (SQL): A Practical Introduction. Blaxwell, Oxford.

Eom S.B. and Lee S.M. 1990. A survey of decision support system applications (1971-April 1988). Interface 20(3): 65–79.

ESRI 1996. ArcView Spatial Analyst: Advanced Spatial Analysis Using Raster and Vector Data. Environmental Systems Research Institute Inc., Redlands USA.

Food and Agriculture Organization (FAO). 1970. Soil map of the world, scale 1:5000000, Vol. I–X. United Nations Educational, Scientific, and Cultural Organization, Paris.

Frantz F.K. 1995. A taxonomy of model abstraction techniques. In: Alexopoulos C., Kang K., Lilegdon W.R. and Goldsman D. (eds), Winter Simulation Conference Proceedings, December 3–6. Arlington, VA, USA, pp. 1416–1419.

Geisler R., Klar M. and Pons C. 1998. Dimensions and Dichotomy in Metamodeling. http://citeseer.nj.nec.com/geisler98dimensions.html.

Gorry A. and Morton M.S.S. 1971. A framework for information systems. Sloan Manage. Rev. 13: 55–70.

Heuvelink G.B.M. 1998. Uncertainty analysis in environmental modeling under a change of spatial scale. Nutr. Cycl. Agro Ecosyst. 50: 1–3,55–59.

Ignizio J.P. 1974. Interval Goal Programming and Applications. Pennsylvania State University, Working paper.

Janssen R. 1992. Multiobjective Decision Support for Environmental Management. Kluwer Academic Publishers, Dordrecht.

Janssens I.A., Freibauer A., Ciais P., Smith P., Nabuurs G.J., Folberth G., Schlamadinger B., Hutjes R.W.A., Ceulemans R., Schulze E.D., Valentini R. and Dolman A.J. 2003. Europe's terrestrial biosphere absorbs 7 to 12% of European anthropogenic CO_2 emissions. Science 300: 1538–1542.

Jussy J.H., Colin-Belgrand M. and Ranger J. 2000. Production and root uptake of mineral nitrogen in a chronosequence of Douglas-fir (*Pseudotsuga menziesii*) in the Beaujolais Mounts. Forest Ecol. Manage. 128: 197–209.

Kerhervé B. and Gerbé O. 1997. Models for metadata or metamodels for data? In: 2nd IEEE Metadata Conference Proceedings, September 16–17. Silver Spring, Maryland, USA.1–12.

Kleijen J.P.C. 1987. Statistical Tools for Simulation Practicers. Marcel Dekker, New York.

Kleijen J.P.C. and Sargent R.G. 2000. A methodology for fitting and validating metamodels in simulation. Eur. J. Oper. Res. 120: 14–29.

Kros J. 2002. Evaluation of biogeochemical models at local and regional scale. Ph.D Thesis, Wageningen University, Wageningen, Netherlands.

Kros J., Mol J.P. and de Vries W. 2000. Possibilities for the modeling of C and N sequestration, groundwater recharge and nitrate leaching in AFFOREST. Internal document, Alterra.

Kros J., Mol J.P., de Vries W. and Heil G. 2003. From process to DSS: the development of a spatial Decision Support System for the effects of afforestation on carbon sequestration nitrogen fluxes and groundwater recharge. To be submited to the Scientific World.

Maguire D.J. 1991. An overview and definition of GIS. In: Maguire D.J., Goodchild M.F. and Rhind D.W. (eds), Geographical Information Systems: Principles and Applications, 1. John Wiley and Sons, New York.

Moon G. 1992. Capabilities needed in spatial decision support systems. In: GIS/LIS '92 Proceedings. San Jose, Calf, USA.2: 594–600.

Muys B., Ceulemans R. and Proost S. 2002. Scenario's voor broeikasgasreductie door vastleggen van koolstof en energiesubstitutie: ruimtebeslag, milieu-impact en kostenefficiëntie. Internal Report PB098/41/16.

NCGIA 1992. A Research Agenda for Geographic Information and Analysis. The National Center for Geographic Information and Analysis, Technical Report 92–7.

Neitsch S.I., Arnold J.G. and Williams J.R. 2001. Soil and Water Assessment Tool User's Manual: version 98.1. Grassland, Soil and Water Research Laboratory.Agricultural research Service and Blackland Research Center, Texas Agricultural Experiment Station, Temple, TX, USA.

O'Brian J.A. 1990. Management Information Systems: A Managerial end User Perspective. Richard D. Irwin Inc.,, Boston.

Powlson D.S., Smith P., Coleman K., Smith J.U., Glendining M.J., Körschens M. and Franko U. 1998. A European network of long-term sites for studies on soil organic matter. Soil Tillage Res. 47: 263–274.

Rijtema P.E. and de Vries W. 1994. Differences in precipitation excess and nitrogen leaching from agricultural lands and forest plantations. Biomass Bioenergy 6(1/2): 103–113.

Rowe L.K. and Pearce A.J. 1994. Hydrology and related changes after harvesting native forest catchments and establishing *Pinus radiata* plantations. 2. The native forest water balance and changes in streamflow after harvesting. Hydrol. Proc. 8: 281–297.

Sampson D.A. and Ceulemans R. 1999. SECRETS: simulated carbon fluxes from a mixed coniferous/deciduous Belgian forest. In: Ceulemans R., Veroustraete F., Gond V. and Van Rensbergen J.B.H.F. (eds), Forest Ecosystem Modelling, Upscaling and Remote Sensing. SPB Academic Publishing bv, The Hague, pp. 95–108.

Schober R. 1975. Ertragstafeln wichtiger Baumarten. J.D. Sauerländer's Verlag, Frankfurt am Main.

Sprague R.H. 1980. A framework for the development of Decision Support Systems. MIS Quarterly, December.

Sprague R.H. and Carlson E.D. 1982. Building Effective Decision Support Systems. Prentice-Hall, Englewood Cliffs, N.J.

Sprague R.H. and Watson H.J. 1989. Decision Support Systems: Putting Theory into Practice. Prentice-Hall International, London.

Turban E. 1995. Decision Support and Expert Systems: Management Support Systems. Prentice-Hall, Englewood Cliffs, NJ.

UNFCCC Secretariat 2001. Marrakesh Declaration, the Marrakesh Accords. Press release by the UNFCCC Secretariat, Marrakech, 10 November 2001.

Urban D.L., Acevedo M.F. and Garman S.L. 1999. Scaling Fine-scale Processes to Large-scale patterns using models derived from models: Meta-Models. In: Mladenoff D. and Baker W. (eds), Spatial Modeling of Forest Landscape Change: Approaches and Applications. Cambridge University Press.

Van Orshoven J., Terres J.-M., Willekens A. and Feyen J. 1999. Transfer procedures for model-based agricultural monitoring. In: Symposium Organised by the European Society of Agronomy regarding 'Modelling Cropping Systems'. Lleida, Spain, June 21–23.

Van Rompaey A., Govers G. and Baudet M. 1999. A strategy for controlling error of distributed environmental models by aggregation. Int. J. Geogr. Inform. Sci. 13(6): 577–590.

Van Ranst E., Vanmechelen L., Thomasson A.J., Daroussin J., Hollis J.M., Jones R.J.A., Jamagne M. and King D. 1995. Elaboration of an extended knowledge database to interprete the 1:1,000,000 EU soil map for environmental purposes. In: King D., Jones R.J.A. and Thomasson A.J. (eds), European Land Information Systems for Agro-Environmental Monitoring. European Commission DG XIII, Luxembourg, pp. 71–84.

Watson R.T., Noble I.R., Bolin B., Ravindranath N.H., Verardo D.J. and Dokken D.J. (eds) 2000. Land Use, Land-Use Change, and Forestry. Cambridge University Press, Cambridge, A special Report of the IPCC.

Winjum J.K., Dixon R.K. and Schroeder P.E. 1992. Estimating the global potential of forest and agroforest management practices to sequester carbon. Water Air Soil Poll. 64: 213–227.