

Database of Environmental Decision Support Tools

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ABSTRACT

This chapter investigates modeling and data sources for environmental decision support for local authorities and private managers. A metadatabase of 198 computerized environmental decision tools was collected using a questionnaire with two sequential web-pages of 4+16 questions (<http://tess.ttu.ee/>). Half of the software applications are freely downloadable and well described online. The database contains 42 references reported as ‘forestry’ tools, 50 as ‘agriculture or apiculture’ tools, and 15 targeting to either ‘amenity areas’ or ‘tourism and access-based recreation’.

The most domain-general toolbox, InVEST, integrates models which support management of natural capital, including pollination of crops and production of timber, but is limited in types of natural capital and management situations. Agricultural toolboxes DSSAT and MicroLEIS cover soil quality issues well but ignore management of agricultural landscapes where natural and semi-natural habitats provide wild crop pollination, biocontrol of pests and other services. The most prominent sustainable forestry toolboxes are UBC-FM and NED-2. The latter contains simulation models and qualitative knowledge bases, but complex forest management conditions require more flexible metamodeling approaches. For the management of recreational sites, no integrated toolkit exists. As most of the existing environmental tools support option assessment, future development should address also earlier decision-making steps.

INTRODUCTION

Among several concepts of environmental management, the concept of natural capital (e.g. Hawken et al., 1999) sees the world’s economy as being within the larger economy of natural resources and ecosystem services that sustain us. Only through recognizing this essential relationship with the earth’s basic resources can businesses, and the people they support, be sustained in the long term.

In practical implementation of natural capitalism, one possible constraint is the question of ownership and hence responsibilities for management. Most natural capital in the biosphere and its services remains a common good, so that market forces fail to regulate its sustainable management effectively.

Scale of Environmental Management Problems

In a simplified scheme, private and common issues project as local and widespread issues, respectively. Market failure can be explained as the failure of local investments to generate local benefits. For instance, a company which invests in producing atmospheric oxygen will never benefit from ordinary market forces. At the same time, market forces usually fail to hinder a company in the introduction of alien species. However, widespread drivers create also local consequences (Figure 1).

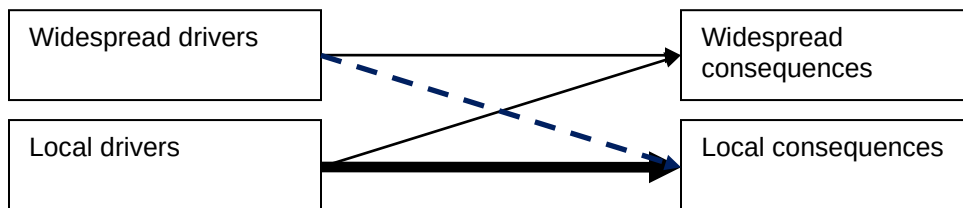


Figure 1. Interactions with widespread issues limit the efficiency of local actions (dashed arrow)

Nevertheless, many field-scale investments to natural capital still give significant field-scale benefits. For instance, fertilization of soil is a typical investment to natural capital which gives returns to the field manager. To facilitate environmental management, we created a database of decision support tools which was targeted on activities where local ecosystem management decisions bring direct benefits to the manager via improved ecosystem services. Some ecosystem services, such as genetic resources and primary production, are essentially global. However, services such as provision of materials and pollination have great local significance (Figure 2). To promote health of ecosystems, the database was targeted on the management of ecosystem services which generate local benefits.

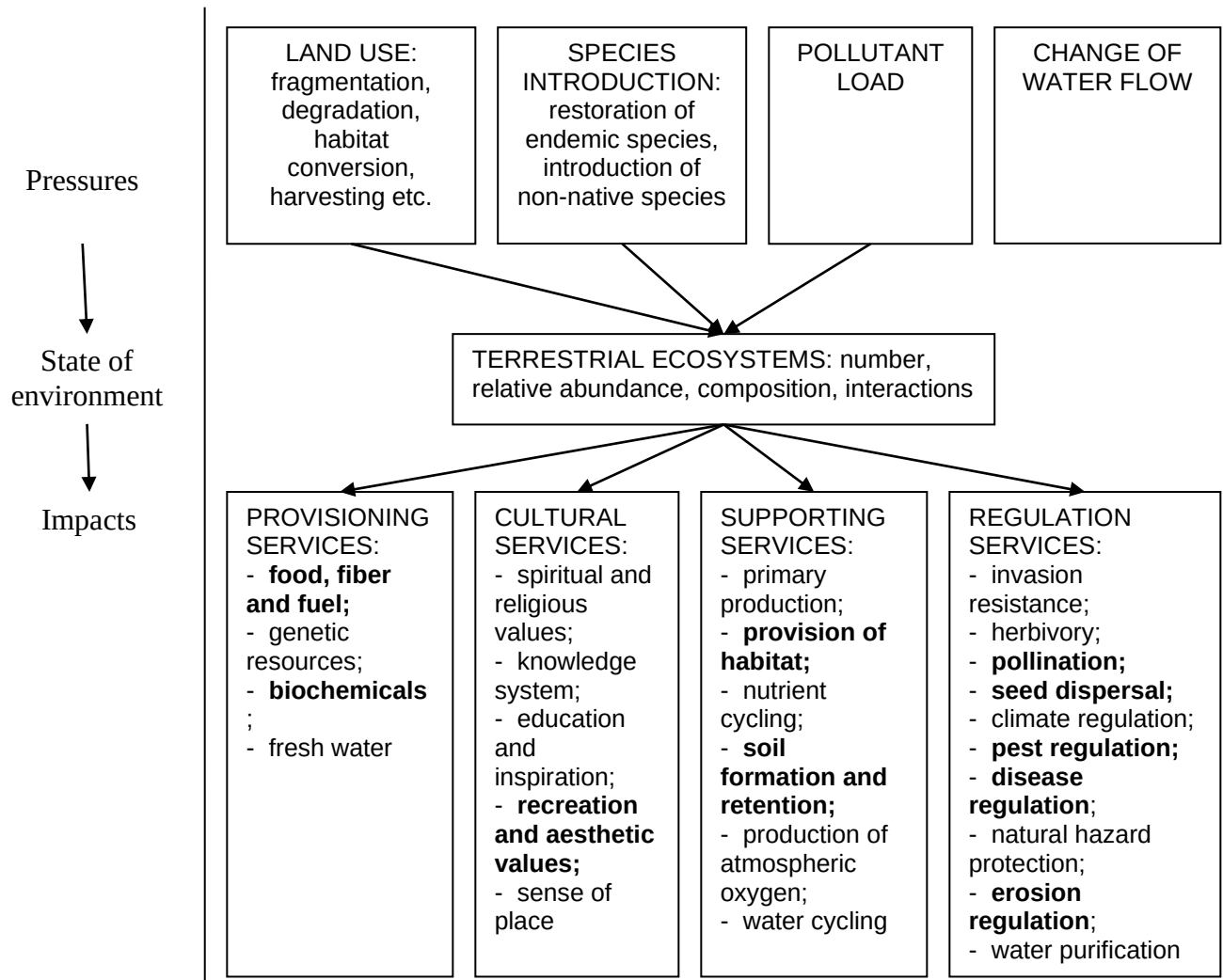


Figure 2. A representation of ecosystem services in the DPSIR framework. Bold font indicates services which generate mostly local effects and therefore where local management applies.

Beyond the “tragedy of the commons”, several other obstacles hinder sustainable management of ecosystem services. Short-term (tactical) interests often compromise long-term (strategic) interests. Ecosystem health is usually a long-term issue, requiring strategic planning. Due to natural buffers, the consequences for ecosystem health of different management scenarios tend to lag. Managers therefore need tools to assess ecosystem health issues strategically. We identified three economic areas where sustainable local ecosystem management might bring immediate benefits: farm-scale agriculture, estate-scale timber production, and on-site management of recreational objects (Table 1). The aim of the database was to identify information tools for these management challenges across the entire EU.

Table 1. Areas of interest represented in the TESS database

Economic	Scale	Target	Output	Major factors
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area		groups		
Agriculture	Farm	Farmers	Sustainable crop and fodder production issues: soil maintenance, fertility, health . Field factors limiting pests.	Erosion. Drainage. Irrigation. Pollinators. Chemicals. Cultivation structure. Buffer strips. GMOs. Pollination. Biocontrol. Weather and climate.
Forestry: timber production	Estate	Private forest owners and managers	Sustainable timber production. Forest health	Tree disease factors. Biocontrol agents. Drainage. Irrigation. Harvesting options. Storm and fire resistance. Climate change
Nature recreation: hunting, fishing, birdwatching, hiking, walking, picking, riding	Recreational site	On-site tourism operators, local land-owners	Maintenance and improvement of the leisure area: production of forest game, production of fish in a small lake, number of birds valuable for watching, attractiveness of the area, availability of forest fruits	Habitat requirements, Effects of pollutants, Hunting and fishing rate, tramping, garbage, number of people, behaviour of people. Climate change from travel.

Information Needs

Chapter 3 shows that local environmental managers have good knowledge on most ecosystem services, but require information on wild species and habitats. Hence, although all ecosystem health aspects were considered, our work targeted especially wildlife as well as natural and semi-natural habitats.

In terms of ecosystem services, commonly required information included that relating to water, wild meat and fish, and fibre (e.g. timber), disaster management (e.g. floods), and capacity for tourism and recreation. Less commonly required was information on wild plants and fungi, cultivated crops, soils and impacts of tourism and recreation (see Figure 3 and Table 9 in Chapter 3). However, to achieve completeness of the database, these aspects were still integrated to the database of models.

Figure 3 shows that there was very great variation in the availability of necessary information (see also Figure 12 in Chapter 7). The Czech Republic, Germany and Hungary stood out in having most of their needs met, whereas Austria, Bulgaria, Latvia and Malta were being especially poorly served. Information requirement on ecosystems for provisioning (crops, medical, biofuels), regulating (flood/fire/disease hazards) and supporting (water/air/ soil quality) services was especially variable, whereas information on cultural services (amenity, recreation, tourism) was generally in high demand (except for Italy, which was most interested in natural hazards). Information on biodiversity (protected and harmful species and habitat maps) was also generally in high demand, except for Italy and Lithuania.

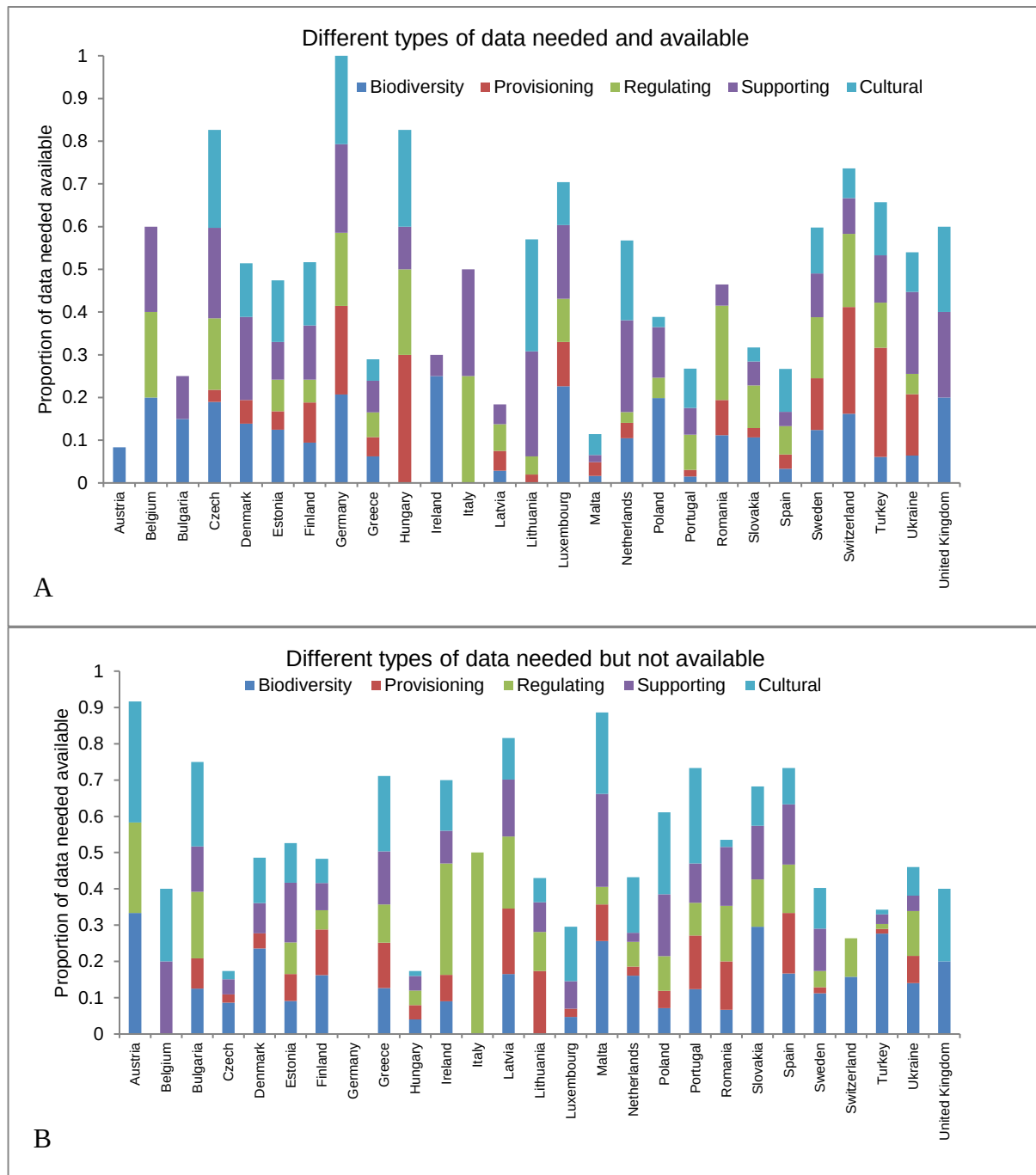


Figure 1. The proportions of different types of data needed by local administrations to make environmental decisions. A Data which were available. B Data which were not available.

Chapter 4 indicates that local land-managers use the internet weakly while local authorities use GIS well, and that local authorities in many Western European countries have high digital enablement (see also Figure 11 in Chapter 7). However, there is a question of whether the digital decision support should be focused to these countries or rather to countries with good biodiversity status. The project therefore did not focus any particular group of member states.

Chapters 3 and 4 also noted that local governments were especially interested in socio-environmental issues. Hence, while compiling the database, conceptually broad environmental models, containing economic terms and socio-cultural dimension, were given special attention.

Environmental Decision Support Systems

Solving widespread environmental problems, such as climate change, extinction of species, or pollution of seas, depends very much on policy (Low and Heinen, 1993). At the same time, successful management of local environmental problems, including soil fertility or forest resilience, depend much on informing about predicted consequences. Among other sources, such information is provided by environmental decision support systems (EDSS). This chapter reviews the existing EDSSs for local stakeholders.

EDSSs apply computerized statistical/mathematical models for conceptually simple but computationally demanding data management, make predictions through simulation, deal with multiple criteria and multiple objectives, and optimize (Walker, 2002). In addition to statistical/numerical models, EDSS may involve geographic information systems, artificial intelligence techniques and environmental ontologies (Poch et al., 2004). In short, EDSS supplies information and knowledge for environmental decision-making.

After concluding that flexibly designed EDSSs, emphasizing reputation and social contracts, could improve local and short-term management decisions, one may well ask how? How, in principle, can computers actually provide information for decision-making?

Instead of just substituting the human mind, an EDSS should add some capacities for a human decision maker (Sturtevant et al., 2007; Makowski et al., 2005). Typically, an EDSS simulates the future, giving a human user a more adequate decision-making ability. As for EDSS, simulation of the future has also been proposed as a primary function of human consciousness (Schacter & Addis, 2007). Viewing a human mind as an independently adapted and powerful decision making machine, how can a computer assist it?

Emery (1987) proposed that humans have an astonishing ability to recognize relevant patterns among many factors involved in a decision making, recall from memory relevant information on the basis of obscure and incomplete associations, and exercise subtle judgments, whereas a computer is much faster and more accurate in handling massive quantities of data. Thus, he proposed the goal of a DSS to be to supplement the decisive powers of the human with the data manipulation capabilities of the computer.

Decades later, the architecture of human brain still beats computers in most aspects, including highly organized network of many diverse processing units (neurons), diversity of signalling mechanisms (chemical, electrical), fuzzy signal transmission, fault-tolerance and flexibility, parallel and distributed processing, metabolism, flexible hardware (life-long neurogenesis and synaptogenesis), and high number of processing elements (over 10^{14} synapses, Table 2). In contrast, modern computers possess only a single or few processing units, only electrical signals, only binary switches, only static, non-learning hardware, only sequential processing, and a lower number of processing elements (transistors).

Table 2. The human brain and computer compared.

	Human brain	Computer
Guiding principle	Network of a large number of diverse processing units	Single powerful processing unit
Signal types	Diverse chemical and electrical signals	Single type of electrical signals
Transmission standard	Continuous variability of diverse state characteristics of neurons and synapses (polyvalent and analogue-digital switch)	Binary (digital) switch
# of elements (order of magnitude)	# of synaptic connections: 10^{14}	# of transistors: 10^9
# of processors (order of magnitude)	# of neurons: 10^{10}	# of CPUs: 10^0
Error management strategy	Adaptive	Prefixed, correct
Type of processing	Parallel and distributed	Sequential

However, allocation of a large number of transistors for a single task, such as sequential binary computing, can provide significant assistance for a human user. As far as processing is concerned, the output of computers also is highly reliable. So the findings of Emery (1987), that the main use of computer is assistance of humans in data processing and analysis, as well as sequential arithmetic and logical operations, remain valid.

Even networked computers have added few new qualities yet. Over 10^9 computers around the world form a higher organizational structure, the internet, which is to some extent commensurate with the brain, having features of life such as growth, adaptation, and response to stimuli. However, due to its extremely decentralized nature, the internet lacks a predesigned, coordinated, concise organization structure. In an EDSS context, as well as the ability to collate data from distributed sources, a main advantage of the internet is its potential capacity for distributed computing, enabling e.g. modelling grids.

The strong computational power to analyze large databases and to carry out complex calculations enables computers to simulate results of management option effectively. This explains the explosion in both number and complexity of environmental management models, especially numerical simulators, in the last few decades (e.g. Poch et al., 2004).

Arithmetic computations are performed by e.g. predictive models and optimization models (Poch et al., 2004). In addition, option assessment is complemented nicely by visualization tools (e.g. Werner et al., 2005).

A Toolbox Approach

According to the range of application, EDSSs could divide into specific and generic tools. Specific tools address concrete management questions in limited preconditions. For instance, the AZODYN (Jeuffroy & Recous, 1999) model assists optimization of nitrogen application to wheat. In contrast, generic tools address various types of problems, applicable in large geographical areas, various time frames etc. For instance, the Soil and Water Assessment Tool (SWAT, Engel et al., 1993), is applicable worldwide to predict transport of water and chemicals in soil, groundwater and surfaces waters, thereby supporting various decisions in agriculture as well as in soil and water protection.

With respect to assistance for various decision steps, as well as in subjects and other criteria, contemporary environmental management tools remain fragmented. The availability of a large variety of such tools challenges a user, who must search for suitable tools, choose between them, and apply several tools concurrently. Hence, several authors (Argent & Houghton, 2001; Hofman, 2005; Moore & Tindall, 2005; Poch et al., 2004; Makowski et al., 2005) have proposed that further development of EDSSs

depends on the integration of various sources of knowledge, intelligent techniques and numerical tools. Such development of generic tools leads to the idea of a future universal environmental management supertool, integrating all relevant small models, and addressing all management situations. However, our world is too complex to expect from an EDSS the solutions for every concrete domain-specific management question (Derry, 1998; Makowski et al., 2005; Huang & Chang, 2003; Yu, 1991; Walker, 2002). Hence, potential attempts to build a universal environmental management supermodel would probably fail.

On this basis, Sturtevant et al. (2007), Makowski et al. (2005), Todd & Benbasat (1999) and Belardo et al. (1994) propose a toolkit approach which builds on existing and readily adaptable modelling tools. They suggested focusing on conceptual modelling, finding the tools and information to answer decision-making questions, and then ensuring that an interacting suite of domain specific tools informs the global objectives of the decision-making process. Thus, compared to a simplistic (i.e., one domain-specific forecasting tool) or a fully integrated (i.e., an interdisciplinary but case-specific model) modelling approach, a more adaptable alternative seems a toolkit of domain specific decision support tools. Which types of tools should such toolkit contain?

Wrisberg & Haes (2002) view decision making as a sequential process, containing issue definition, criteria setting, option generation and option assessment. Each of these steps requires different tool types. Issue definition and criteria setting need checklists (e.g. Lindenmayer et al., 2008) and dialectic tools (Jarupathirun & Zahedi, 2007). Option generation, in contrast, benefits from creativity support, provided by creative virtual environments (Wierzbicki & Nakamori, 2005; 2007).

Reasoning Tools

Option assessment, the most widely addressed decision step among EDSSs, benefits from rational logical reasoning and complicated arithmetic computations (Piirimäe, 2011). Logical reasoning emerges from qualitative models (Nuttle & Bouwer, 2009), almost synonymously also referred as Bayesian networks (e.g. Ticehurst et al., 2007), artificial neural networks (Wieland et al., 2002) or environmental ontologies (e.g. Ceccaroni et al., 2004).

Ceccaroni et al. (2004) invented the OntoWEDSS model, which augments classic rule-based reasoning and case-based reasoning with a domain ontology. OntoWEDSS assisted the diagnosis of faulty states of wastewater treatment plant. The authors foresaw future EDSS as a great reasoning system, composed of digitally signed ontologies, i.e. rules and logical statements.

Bredeweg et al. (2007 and 2008) designed Garp3 as a qualitative simulation model which aids river basin management. They recommended construction of a library of model fragments to reason the behaviour of a set of systems belonging to a given domain. From these fragments (conditional statements), the Garp3 model engine simulates management scenarios. In the theme of sustainability, Salles et al. (2008) have already started building a library of qualitative conditional statements.

Will an approach of computerized qualitative reasoning successfully aid decision-making in future? Inevitably, such tools require the transforming of fuzzy human ideas into formally specified representations which work as reasoning building blocks. However, comparison between computers and human brains suggests that digitalization of human fuzzy ideas through advanced “hardware” architecture might merely simplify them.

Apart from the critique of formalized statements, could computers assist humans in reasoning with such qualitative fragments? Perhaps, but if so the human mind may then struggle with the necessary logic.

Logic is not a strength of human reasoning (Stenning & Lambalgen, 2008). The human mind has evolved reasoning schemes as strategies to solve problems. These reasoning schemes need not necessarily follow formal logic or principles of rationality. Defining rationality as an ability to distinct between valid arguments and fallacies, laboratory experiments have shown human reasoning to be rather irrational and very poor at obeying the rules of rational systems (Wason, 1968). For instance, most humans fail to obey the simplest logics of *modus tollens*. Are other reasoning schemes, such as heuristics, more adaptive?

Normatively correct reasoning may facilitate more accurate decisions but demand too much computing capacity (Oaksford & Chater, 2001; Verschueren et al., 2005). As human operational memory remains limited, we adaptively use subnormal prescriptive rules which often lead to incorrect conclusions, even in solving simple logical tasks.

Due to our limited operational memory, the solution to the problem of logical errors will not come through improved thinking. Instead, logical reasoning might be improved by computerized tools which operate with high accuracy and large operational memory. On that basis, Sturtevant et al. (2007) and Klein & Methlie (1990) recommend prioritizing EDSS development for conceptual modelling.

Klein (2008) found that very often the solution of decision problems results from the combination of computation and reasoning. A computer can work as a prosthesis for providing missing analytical resources, then simulating consequences of both seemingly simple and complex management options. Such a perspective foresees an EDSS as a software tool which works in close relationship with the human mind. Among other functions, the computer might critically evaluate human beliefs. In combination, the user might present rules with which the computer delivers logically correct outcomes.

Hence, in future, EDSSs might potentially enhance environmental management by providing formal logics. However, possible loss of valuable information in digitising conditional statements is an important constraint that must be taken into account.

Support for Intuitive Reasoning

While powerful and rational EDSSs have been spreading fast, they still hardly influence real decisions and user behaviour (Walker, 2002). Reasons may involve decision-making mechanisms in human minds.

Human consciousness can be characterized as a reasoning system which operates on rules and procedures, acquired via instructions (Carruthers, 2007). Hence, a typical EDSS communicates primarily with our consciousness. In contrast, successful entrepreneurial decision makers still tend to rely on intuition (Paprika, 2008; Khatri & Ng, 2000; Agor, 1986; Harper, 1989).

Conscious will itself may be an illusion. Wegner (2002), Carruthers (2007) and Gazzagina (1985) demonstrated that our impulses to act are activated unconsciously. More specifically, our mind-reading system might lack any access to events that take place in practical reasoning system. As a result, our consciousness can only, after the fact, report the effects of intuitive reasoning and resulting behaviour.

Consequently, if an EDSS does not affect our intuitive reasoning system then it may fail to direct our actions. Hence, successful design of EDSSs may depend on effective coupling with intuition. How could that be achieved?

Earlier research reports tended to suggest that the use of intuition is generally inferior to rational models (e.g. Dawes et al., 1989; Schoemaker & Russo, 1993). Some reports specify that intuition works relatively well in extreme time pressures (Dane & Pratt, 2007). However, in solving strategic questions, which are typical in environmental management, intuition might work too quickly, producing inaccurate decisions (Dane & Pratt, 2007, Carruthers, 2007). Thus, Dane & Pratt (2007) suggested that poor intuitive reasoning should be hindered by more formalized decision-making procedures. A successful EDSS might slow the decision-making process, e.g. by splitting it into several steps.

On the other hand, several recent studies (overview in Dane & Pratt, 2007) indicate that intuition might actually reason with a very high accuracy. For example, computing successful decisions about cooperation requires very complex economic models. Without computer aid, humans can not easily optimize social cooperation consciously and indeed tend to show irrationally selfish behaviour. In contrast, intuition tends to guide towards cooperative and sustainable behaviour. Intuitive goals can even be activated and operate without the participant's awareness (Bargh et al., 2001). Thus, an intuitive goal of cooperation works against selfish decisions. For instance, unobtrusive priming towards a goal of cooperation leads humans playing the role of a fishing company to compromise their own profits in order to replenish a fish population (Bargh et al. 2001).

Some evidence of the power of intuitive reasoning originates from the theory of computational complexity. While conscious reasoning processes verbal information, intuition must process sensory signals, including visual information, requiring much higher computational capacity (Wierzbicki & Nakamori, 2005).

Thus, compared to conscious reasoning, intuition may work as an even more effective reasoning tool. Therefore, instead of suppressing intuitive reasoning, the development of EDSS should seek possibilities to improve such unconscious reasoning processes. Human intuitive reasoning is supported by case-based reasoning tools (Ceccaroni et al., 2004; Chen et al., 2008) and training tools (Klein, 2008).

MODEL METADATABASE ARCHITECTURE

The architecture of the database considered the need to organize and integrate various decision support tools into three toolkits: forest health toolkit, field health toolkit and recreational site management toolkit.

Complexity

The question of system complexity constituted one of the major challenges in the TESS project. Addressing numerous environmental problems all over the EU as well as integrating different model approaches requires rather complex thinking. Moreover, target groups such as local managers will include persons without special training or education in environmental issues and modelling. Therefore, persons with relatively little training need to be able to work with a given toolbox.

For considering system complexity, we adopted the model of hierarchical complexity (MHC, Commons et al. 1998) which quantifies the order of hierarchical complexity of a task, based on mathematical principles of how the information is organized. MHC defines at least 14 universal discrete stages of complexity which might also define human cognitive development, regardless of cultural context.

The toolkits should generally operate in no more than formal level which corresponds to the order 10 in MHC (Table 3

Table). Order 10 enables rational and analytical arguing using empirical or logical evidence. Formal logic, however, remains linear and one-dimensional. Order 10 allows relationships between variables, hence correct scientific solutions. More complex models, such as multivariate systems and fuzzy relationships, should be avoided, or require good explanatory support from the system.

Table 3. A framework of complexity for the TESS project

Cognitive framework (from Commons 1998)	Modelling framework (types of model)	Application in TESS project
10. Formal	Formalised models	Operation of toolkits and ecological models within these
11. Systematic	Metamodels	Architecture of TESS metamodel and its toolkits – organises the application of ecological models
12. Metasystematic	Integral frameworks	TESS project implementation

While the toolkits operate in Formal order (10), their architecture and TESS metamodel are in Systematic order (11) which include multivariate matrices and contexts. TESS project itself, organizing metamodels, operates in the 12th order, which is metasystematic, for constructing supersystems, multi-systems and metasystems out of disparate systems.

Which are the best criteria for classifying environmental decision support models? After visualizations and conceptual models, research communities differentiate mathematical models predominantly by temporal and spatial complexity, geographical limitations, decision types, environmental themes, computational and technological approaches (e.g. Jörgensen & Bendoricchio, 2001). To select the most useful of these, we needed model classification metacriteria, i.e. criteria for classifying criteria. TESS classifies models in terms of complexity and technological approaches to facilitate the design of decision support systems, but also very importantly by environmental themes and decision types needed by users.

After finalizing the general architecture of the metamodel, further classification was required. As the final aim was to get integrated toolkits, we classified the tools according to their integration prospects, i.e. vertical complexity. The resulting classes comprised: ‘conceptual framework’; ‘metamodels (integration concepts)’; ‘model types’ (including ‘computer programmes’ as a higher rating ‘raw models’ such as regression formulae at a lower rating; ‘variables’; and ‘data’ (Figure 4).

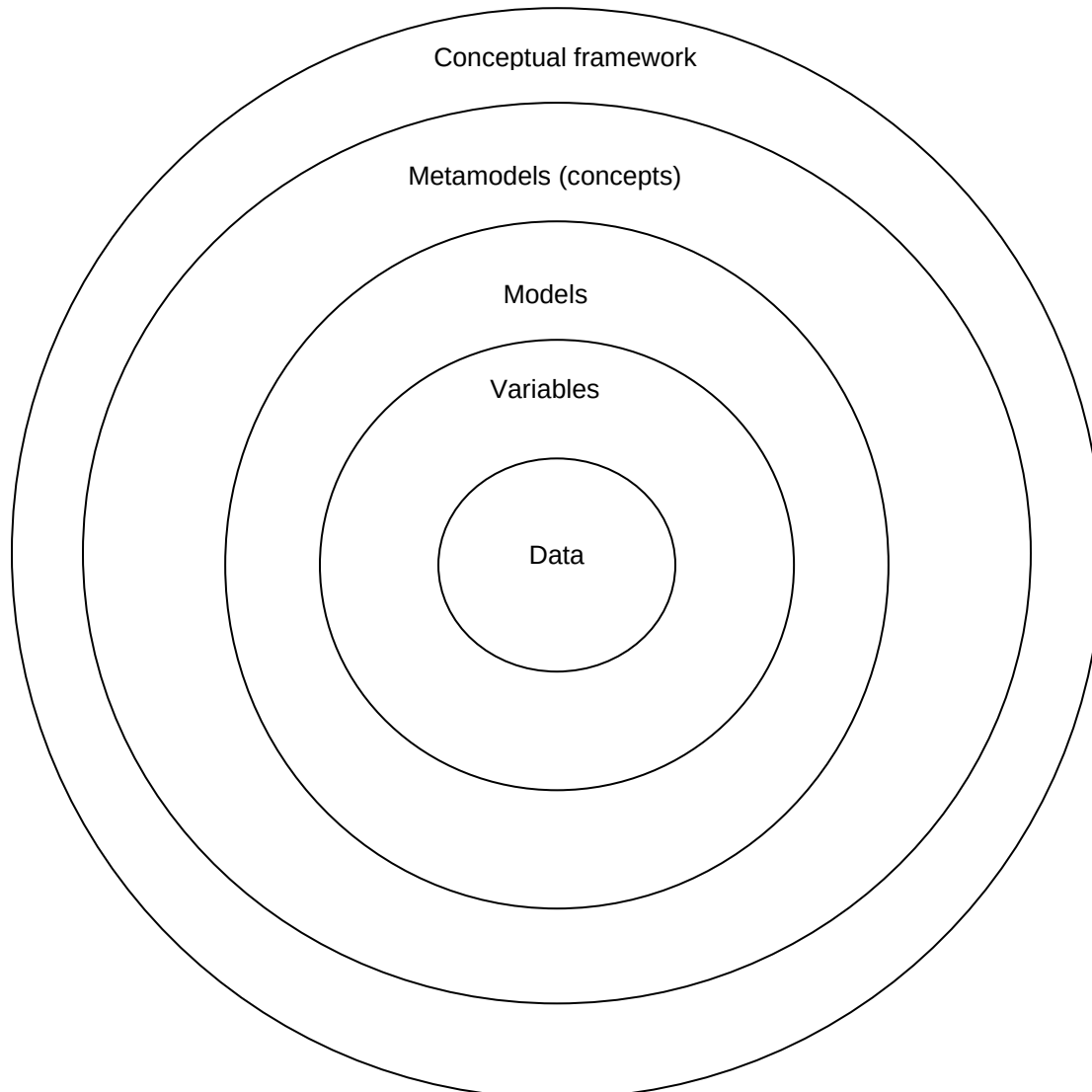


Figure 4. A holarchic organisation of knowledge for local ecosystem management.

This classification is a holarchic system (hierarchy of holons) in which each holon is both a part and a whole (Koestler 1967). The models form a holon, which is an organization of variables, while models themselves could be organized to metamodels, which is one holon higher in the knowledge organization. Such system correlates approximately with MHC and the framework of complexity in TESS.

Assessing complexity and technological approaches in models is important for their potential as building blocks in toolkits. The most advanced models are user-friendly smart computer programmes, able automatically to calculate outputs from input data and display them in a user-friendly context. TESS seeks conceptual solutions for integrating models to toolkits and later to automated DSS. For instance, SILVA is an individual tree-oriented management software model, but needs integrating with statistical forest management models. We should also consider that beyond providing solutions for management situations, a main benefit of management models might be user education (Walker, 2002).

Some environmental management themes lack decision support programmes. In these cases we need to search for research findings such as published regression formulae and other information that can predict outcomes of processes. Typically, this raw information is not in a named model and needs programming to integrate to toolkits and computer models. Our task is to set the programming strategies. For instance, if user-friendly models for game management are missing, an extensive literature review could reveal quantitative models determining population density of and income from various game species. We could then develop strategies to integrate these raw game population models to a relevant toolkit.

Work at lower levels of complexity may be needed to feed the designated toolkits. In spite of literature search, some raw models will probably be missing or inadequately parameterized for environmental management. Such knowledge gaps require mapping so that appropriate models can be developed. If crucial data are missing, hindering proper functioning of models, it may be necessary to stimulate research to search for or estimate necessary parameters, constants or other background data.

Commensurability

As described above, the classification of models for TESS depended partly on the need to integrate commensurable models and databases to generate hybrid supermodels and relational databases. For this, GIS data from different geographic locations need to be transformed and link to a standard pan-European platform. As much as possible and relevant, various regression models need to integrate to bigger units such as Forest 5 (Robinson & Ar, 2003). A group of models which enable technical integration and pipelining is defined as commensurable and may be expected to fall to a distinct model cluster. In contrast, incommensurable models should classify to different clusters, but may possibly be linked either in user-mediated or holistic ways.

EDSSs might differ according to spatial and temporal criteria. Temporally, model categories comprise static (lumped), steady-state and dynamic models. The latter class, in turn, often splits in short-term (tactic) and long-term (strategic) models. Spatially, models divide into 0D (non-spatial), 1D (linear), 2D (planar), and fully 3D (spatial) models. The subdivisions might include small-scale and large-scale models, although the TESS metamodel focuses on local models.

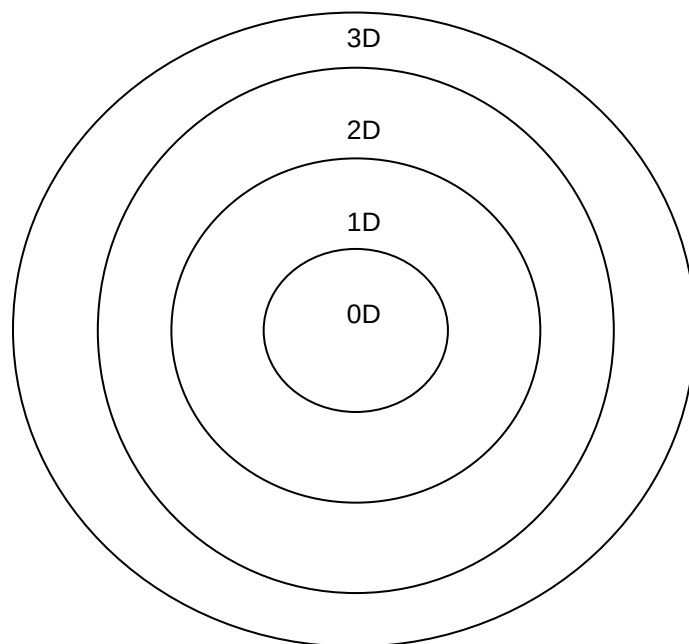


Figure 5. The holarhic relationship between models of different spatial type – all appearing in principle commensurable.

A more complicated cluster can include simpler components. For instance, a spatial model can include non-spatial components (Figure 5): a complex spatial model might be commensurate with spatially

simpler models. The principle of commensurability suggests that the most spatially complex model defines the spatial complexity of the entire cluster. The resolution of the cluster should arrive analogously.

Based on graphical technology, spatial models divide between raster models (including cellular automata) and vector models. Raster models involve cells of predefined size and location while vector models relate polygons. In principle, these two graphical solutions are commensurate, but in practice the conversions and pipelining can cause loss of information and increase of computational requirements, which makes them practically rather incommensurable.

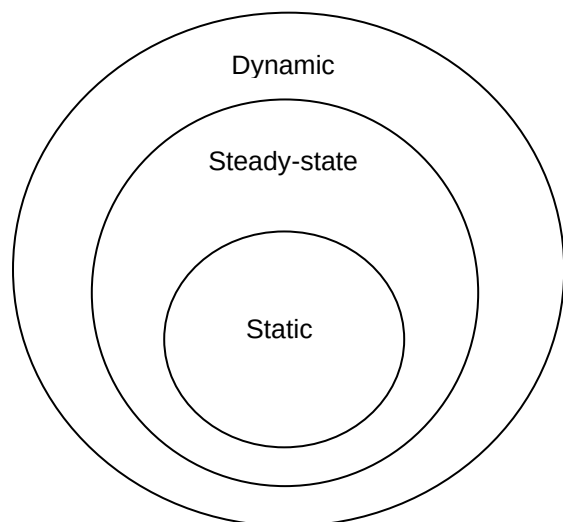


Figure 6. The holarchic relationship between models of different temporal types – all appearing in principle commensurable.

Applying holarchic logic, static (time-independent models) can join time-dependent models, while steady-state models can also be included in a dynamic cluster (Figure 6).

In conclusion, in spatial and temporal terms, vertical complexity of a model cluster should be defined by vertically the most complex model within the cluster. e.g., if the most complex model operates spatially in 2D then the entire cluster should operate in 2D. Similarly, the temporal resolution of the cluster should be defined by the resolution of the finest model. For instance, if the finest model in the cluster has a time-step of one day then the resolution of the entire cluster should be also one day.

However, short-term and long-term processes and management issues can differ in other ways (e.g. Poch et al., 2004). Short-term issues involve optimization of operational management and tactical problems with short feed-back. In contrast, long-term issues may involve capital investments, strategic planning, design and development. Long-term models are able to show environmental consequences of management alternatives. Therefore, it might appear necessary to divide the models between short-term and long-term clusters. Some models, however, might apply in both clusters.

In addition to temporal and spatial mismatches, pipelining of models might be hindered by computational incommensurability. Individual-based (agent-based) models contrast with regression models. Individual-based situations (such as descriptions of state of each individual in a population) readily provide statistical estimates of uncertainty (e.g. for population density) and can predict beyond the limits of original estimation. Regression models can simplify and unify numerous diverse events, but assume that individual differences, fluctuations and exceptions are negligible in determining the system outputs. However, simulation approaches and management situations of these two model types tend to differ. In practice, regression models tend to be used in larger systems with enormous number of individuals or individual events. In contrast, individual-based models assume that individual differences do not average out but can generate significant changes to the entire system and they apply different set of approaches such as game theory, Monte Carlo Methods etc. In practice, such models easily compute smaller systems

where the number of e.g. individual trees or animals is relatively low. Such fundamental differences suggest the splitting of all models into regression and individual-based clusters.

A technical challenge might be pipelining of several high-resolution models which independently run fast enough but together slowly. For instance, a static model with high spatial resolution and a 0D model with high temporal resolution might work well independently but a cluster of high temporal and spatial resolution might malfunction when pipelined. One solution might be user-defined compromise. A simpler solution might be to exclude very high-resolution models from pipelining.

In conclusion, each of three major classification criteria split the models into two clusters, so that models as a whole divide into eight clusters (Table 4

Table 2). However, computationally demanding models cannot be assumed to be easy to unite functionally within any cluster.

Table 2. The classification of models into commensurable clusters.

Classification criterion	# of classes	Classes
Graphical mapping technology	2	a) vector graphics b) raster graphics
Time horizon	2	a) short-term b) long-term
Simulation technology	2	a) regression b) individual-based
Total	8 model clusters	

User Needs

In a decision support system (DSS), technological classification and clustering of models might differ from the appearance of the system to users. As described above, the TESS metamodel splits functionally, according to user needs, into three toolkits: a Field Health Toolkit, a Forest Health Toolkit, and a Recreational Site Management Toolkit. Each toolkit, in turn, consists of several tools. Each model can work in more than one toolkit. Each toolkit can involve more than one model cluster which might be linked holistically (instead of algorithmic links, a toolkit might simply involve links to start-up menus).

If relevant, the interfaces of toolkits might classify models to information classes such as atmospheric class, hydrospheric class, geological class (including soils), sessile class (plants), locomotive class (animals), economic class, sociocultural class etc. However, each toolkit should also clearly indicate all incorporated models.

DATABASE CONTENT

Tool Collection Methodology

A metadatabase of 198 computerized environmental decision tools was collected using a predefined questionnaire. The questionnaire consisted of two sequential web-pages, asking contributors 4+16 questions. The first page (Box 1) asked the most critical questions while the second page collected additional useful information about each model (Box 2). The internet questionnaire was linked to the TESS project website and communicated to TESS project partners as well as other potential contributors.

Model Name and acronym

Web-link.....

Subject:

- Atmosphere including weather (examples: air pollution, noise pollution)
- Water, catchment (examples: hydrological, water pollution)
- Soil and rock (examples: erosion, fertility, compaction)
- Vegetation including fungi (examples: genetics, species, populations, guilds, habitats)
- Fauna (examples: genetics, species, populations, guilds)
- Ecosystem (examples: food chains, natural communities, biotopes)
- Economic (examples: licence fees, markets, fines, taxes, subsidies)
- Social & institutional (examples: legislation, codes of conduct/practice, consultation, conflict resolution, civic activities)
- Socio-environmental (examples: sustainability, climate change)
- Other (please email IST for assistance.)

Ecosystem service management:

- Disease hazards (examples: rabies, malaria, lyme disease, tuberculosis)
- Physical hazards (examples: fires, floods, air quality, water quality, carbon storage)
- Agriculture & apiculture (examples: arable farming, animal husbandry, horticulture, olive production, pollination, biofuels)
- Aquaculture & commercial fishing (examples: salmon farming, ostreiculture)
- Forestry (examples: coppicing, paper, timber, charcoal, cork)
- Wild vegetal products (examples: reeds, fungi, berries, flowers, sap, medical)
- Hunting & angling (examples: falconry, hounds, shooting, game fishing, coarse fishing, spear-fishing)
- Tourism and access-based recreation (examples: rambling, climbing, skiing, boating, camping, golf, dog-walking, horse-riding)
- Amenity areas (examples: parks, gardens, road verges, railway embankments)
- Biodiversity conservation (examples: protection, reserves, re-introduction, alien species)
- Heritage conservation (examples: archeology, buildings, site erosion)
- Other (please email IST for assistance.)

Short model description.....

Contact person (name, e-mail)

Modelling paradigm

- Simulative prediction
- Optimization process
- Multi-criteria analysis
- Other: please specify
(e.g. dialectic EDSS, creative space, expert system etc.)

If simulative prediction is used, is the approach:

- Rule-based (e.g. qualitative reasoning, rules, rates, environmental ontologies)?
- Regression (statistical, empirical etc.)? deterministic or stochastic outputs?
- Individual/cell-based (agents)? deterministic or stochastic outputs?
- Other

Vertical complexity:

- Published statistical relationship (regression, rate or other formula)
- Software tool, packaging one or more formulae for practical use
- Decision support system, organizing or enabling several modelling tools

Computing platform

- Single computer/PDA
- Internet-linked Servers,
- Distributed Processing (e.g. GRID)

Operating system(s)

- Microsoft (Windows, Silverlight, .net etc)
- Unix, Linux or other Unix-like
- Apple (e.g. Mac OS)
- Other, please specify ...

Modelling language(s)

Graphical mapping technology:

- Raster-GIS (grids, pixels)
- Vector-GIS (polygons, lines, points)
- Non-GIS

Time horizon:

- Short-term
- Long-term
- Not specified

Geographical applicability area

- Universal
- Region-specific: Specify region
- Other

Sectoral application area:

- Research (descriptive)
- Management
- Education and learning
- Other

User-friendliness

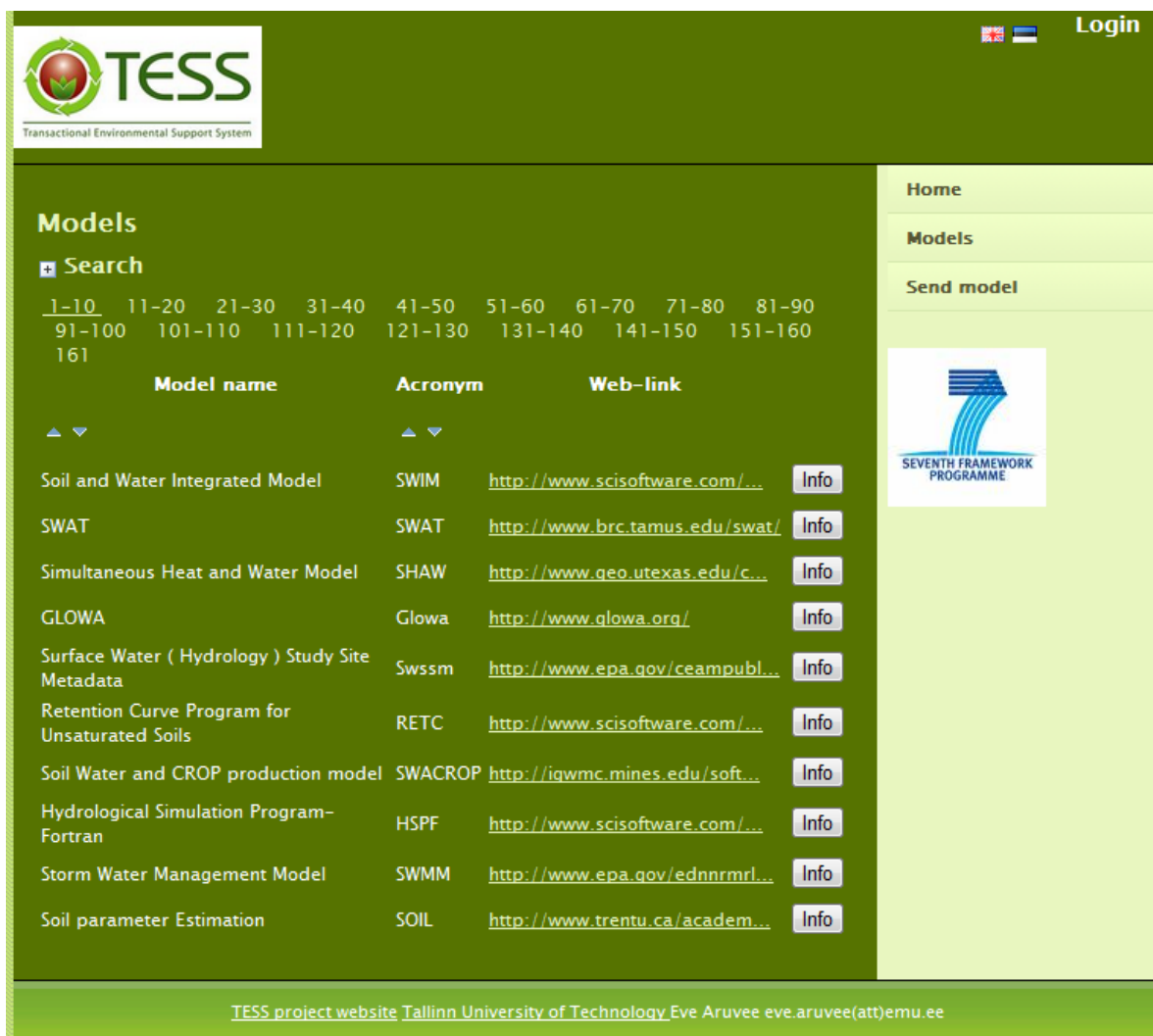
- Easy-to-use
- Expert assistance required

User-provided inputs:

Computational outputs:

Examples of practical application:

The online database (<http://tess.ttu.ee/>, Figure 7) is in MySQL with web-based administration in PHP running on an Apache2 server. The database enables queries, searches and various analyses of metadata.



TESS
Transactional Environmental Support System

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Model name	Acronym	Web-link	
Soil and Water Integrated Model	SWIM	http://www.scisoftware.com/...	Info
SWAT	SWAT	http://www.brc.tamus.edu/swat/	Info
Simultaneous Heat and Water Model	SHAW	http://www.geo.utexas.edu/c...	Info
GLOWA	Glowa	http://www.glowa.org/	Info
Surface Water (Hydrology) Study Site Metadata	Swssm	http://www.epa.gov/ceampubl...	Info
Retention Curve Program for Unsaturated Soils	RETC	http://www.scisoftware.com/...	Info
Soil Water and CROP production model	SWACROP	http://iqwmc.mines.edu/soft...	Info
Hydrological Simulation Program-Fortran	HSPF	http://www.scisoftware.com/...	Info
Storm Water Management Model	SWMM	http://www.epa.gov/ednnrmrl...	Info
Soil parameter Estimation	SOIL	http://www.trentu.ca/academ...	Info

TESS project website Tallinn University of Technology Eve Aruvee eve.aruvee(att)emu.ee

Figure 7. The interface of the TESS database of models, showing status in May 2010.

The project team and other contributors submitted models to the TESS metadatabase using a web-based submission system (<http://tess.ttu.ee/>). The models were collected mostly from Internet, according to the project scope. Of the existing databases, the most significant sources for the database were ECOBAS (<http://ecobas.org>), EPA Exposure Assessment Models (<http://www.epa.gov/ceampubl>), SSG Sources For Environmental Software (<http://www.scisoftware.com/html/products.html>), NASA Global Change Master Directory (<http://gcmd.nasa.gov>) and many other environmental management databases. The Google search engine (www.google.com) was used to find further models. A network of experts around TESS project partners was used to find additional modelling tools. Scanning revealed more than 2400 environmental management software tools.

Of scanned models, models suitable for the database were selected according to the following criteria: (1) scope and needs of the database and the TESS project, focusing on field health, forest health and recreational site management in local scale; (2) quality of models including update time, user-friendliness etc.; (3) availability of models, including availability of metadata on the internet.

Metadata for each model were filed in the model submission questionnaire. However, metadata were mostly collected from web-sites for the models by the project team. Fewer metadata were submitted by the model developers and users.

Tool Types

By May 2010, the database contained 161 models, mostly added by model developers and users. Approximately half the submissions did not record all the metadata that was in the questionnaire. As the architecture of the database and some questions in the questionnaire are conceptually relatively complicated, scope for ambiguous interpretation and classification was also quite high. For instance, criteria within ‘vertical complexity’, ‘modelling paradigm’, and ‘simulative predictive approach’ could be misunderstood by contributors. The project team therefore reviewed information about registered models on the web, and also added another 37 models by May 2011 as a result of their own searches.

Half of the software applications in the database were freely downloadable and well described on the Internet. However, a few models were very poorly described on the internet, in terms of what they were meant for, their mathematical characteristics, and the necessary input variables. These models also mostly lacked specification of output parameters, which is a very important consideration when creating EDDSs.

Contributors specified vertical complexity of their submitted tools in only 138 cases. Most of these tools (113 items) in the database were reported as ‘software tools, packaging one or more formulae for practical use’. The other 23 references were reported as ‘decision support systems, organizing or enabling several modelling tools’. Nevertheless, we later classified most of these 25 models too as just ‘software tools, packaging one or more formulae for practical use’. There is extremely little integration of basic formulae.

Of submitted tools the database contains 42 references which have been reported as ‘forestry’ tools, 50 as ‘agriculture or apiculture’ tools, and 15 targeting to either ‘amenity areas’ or ‘tourism and access-based recreation’ (Figure 8).

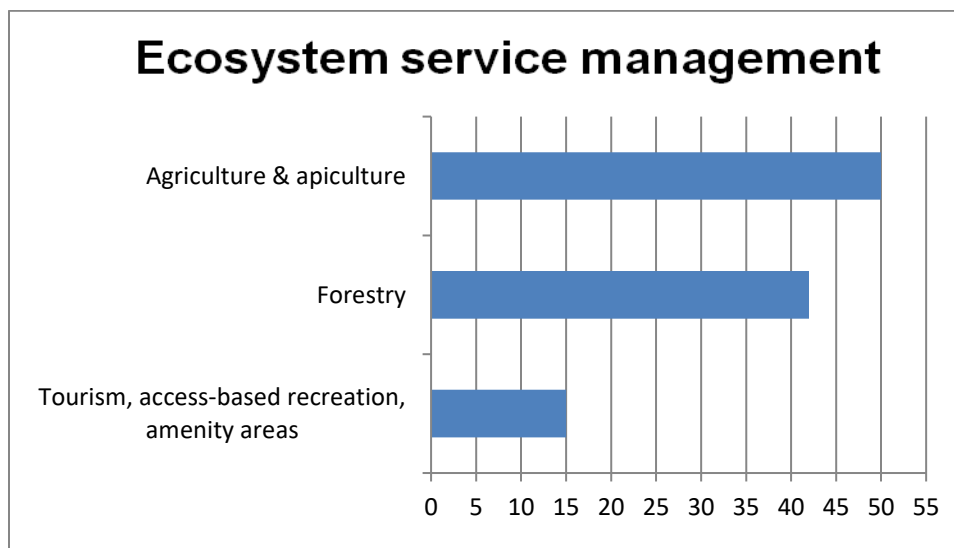


Figure 8. The availability of models for types of ecosystem service management.

Of the submitted models, 36 were reported targeting a long-term time horizon while 36 were short-term. In total 33 models applied raster-GIS while only one model applied vector-GIS. Of various decision support paradigms, we collected 1 expert system, 8 multi-criteria analysis models, 15 optimization processes, 96 simulative predictions and 13 other types. Of simulative predictions, 16 were rule-based systems (e.g. qualitative reasoning, rules, rates, environmental ontologies), 24 were individual/cell-based models, 29 were regression models and 16 were reported as other types of simulative predictions.

GAPS AND RECOMMENDATIONS

Comparing the number of issues identified by stakeholders in Chapters 3 and 7 with the number of models in the database, the best fulfilled needs seem to me in water, geological, economic and ecosystem themes (Figure 9). Social and atmospheric issues are relatively poorly covered. However, as atmospheric issues such as climate change and pollution are mostly large-scale problems, the database for local management has less need of such models. Lack of social models, however, may create an important gap.

Of various management areas, the best met information needs seem to be in forestry, agriculture together with apiculture, and aquaculture together with commercial fishing (Figure 10). The most critical gaps appeared in ‘tourism and access-based recreation’, ‘biodiversity conservation’, and ‘amenity areas’.

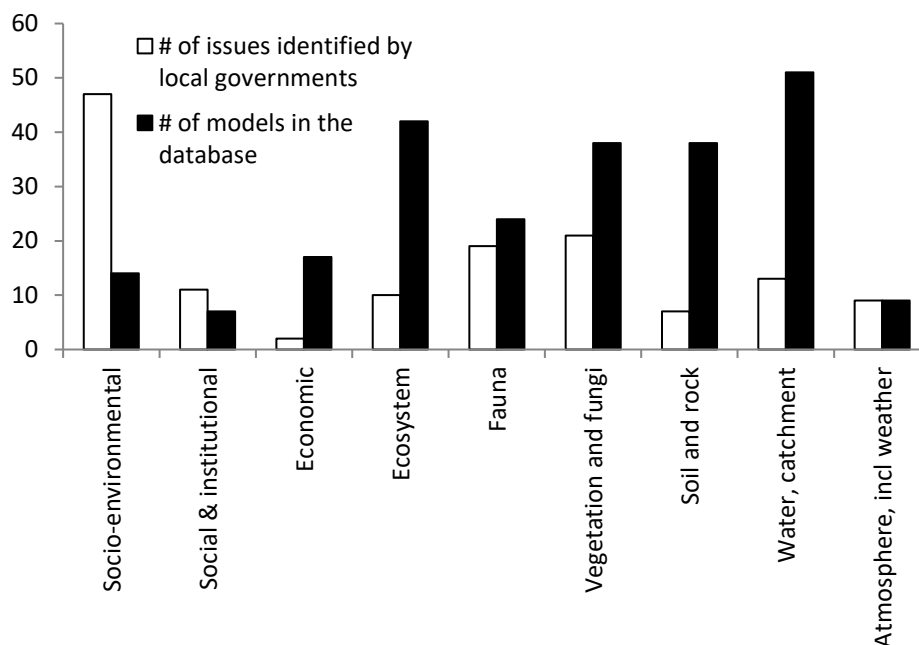


Figure 9. Supply and stakeholder demand for environmental information across subject fields.

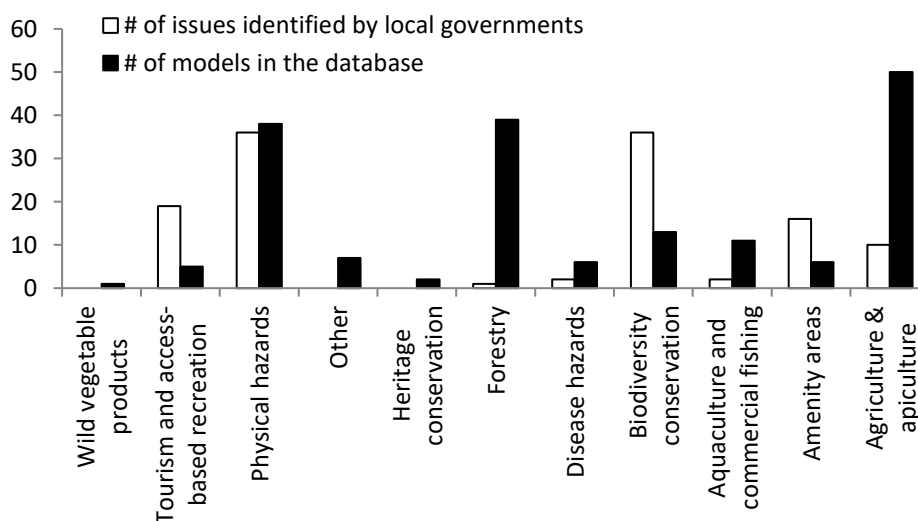


Figure 10. Supply and stakeholder demand for environmental information across management areas.

Agri-environmental Tools

For combating large-scale environmental problems, such as water pollution, climate change and use of fossil energy, farmers often receive agri-environmental payments. In contrast, compensation mechanisms may be neglected for local environmental measures which provide larger, sustainable production yields as well as better product quality. For instance, effective management of soil ecosystems and agricultural landscapes may lead to better ecosystem services: crop pollination, control of pests, nitrogen fixation, soil mineralisation and mollification, mycorrhizal take-up of water and nutrients, erosion prevention.

Of these ecosystem services, crop pollination is described by InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs; Tallis et al., 2008) toolbox which models and maps natural capital. The tool, being developed in the United States, helps users visualize the impacts of potential decisions, identifying tradeoffs and compatibilities between environmental, economic, and social benefits. The individual models in InVEST are very simple. Hence, the toolbox remains limited in its ability to provide effective decision support for the environmental management in the EU. However, the InVEST project is striking for its conceptual comprehensiveness, providing a sound integral framework for the development of more useful versions of the toolbox.

The crop pollination model in InVEST simulates resource needs and flight behaviour of wild bees. The model uses information on the availability of nest sites and flower resources, as well as flight ranges of bees, to map an index of bee abundance, their likeliness to visit crops and the resulting additional crop yield across the landscape.

The crop pollination model serves as a good pilot tool for the management of natural and semi-natural habitats for agricultural benefits. However, InVEST lacks simulation of non-bee wild pollinators. Moreover, these habitats provide other services to farms such as natural biocontrol of pests and (in 2011 at least) require further decision support software. InVEST 2.1 lacks soil management tools, although an agricultural production model is under development.

Of the existing agricultural management toolkits the most prominent are DSSAT and MicroLEIS. The DSSAT (Jones et al., 2003) toolbox incorporates all crops as modules using a single soil module and a single weather module. DSSAT contains models of 17 crops including maize, soybeans, wheat, rice and others. DSSAT can simulate also low-input systems to conduct long-term sustainability analyses. DSSAT has aided decision-making in various including crop management (Fetcher et al., 1991), climate change impact studies (Alexandrov & Hoogenboom, 2001), sustainability research (Quemada and Cabrera, 1995), and precision agriculture (Paz et al., 2001, 2003). Users and developers have validated the toolbox for large geographical areas and many crops. DSSAT allows users to add their own application dynamically to the DSSAT toolbar. Thorp et al. (2008) developed an Apollo system which enables DSSAT models to simulate and analyze spatially variable land management.

DSSAT is a toolkit for simulation. Hence, it lacks other EDSSs such as expert systems, qualitative reasoning, participatory EDSSs etc. For aiding a large variety of management situations, farmers need much more diversified toolkits, such as MicroLEIS.

MicroLEIS, a land evaluation decision support system for agricultural protection (Rosa et al., 2004) supports planning, researching or teaching the sustainable use and management of rural resources, with especial reference to the Mediterranean regions. This agro-ecological system provides a computer-based set of tools for an orderly arrangement and practical interpretation of land resources/agricultural management data. The design philosophy follows a toolkit approach, integrating many software tools: databases, statistics, qualitative approaches, expert systems, parametric systems, neural networks, optimization tools, hybrid approaches, Web and GIS applications, and other information technologies.

In contrast with DSSAT, the flexible MicroLEIS can address a large variety of problems in sustainable farm management. However, neither DSSAT nor MicroLEIS have addressed management of the natural and semi-natural habitats in agricultural landscapes which provide returns to farmers such as crop

pollination, control of pests etc. The InVEST toolbox, in contrast, overlooks soil management issues while addressing wild pollination. Farm management decision support therefore needs a second order integrated toolkit containing the pollination model of InVEST, scenario simulations of DSSAT as well as variable tools of MicroLEIS. However, after the integration of these functions, several agri-environmental issues, such as biocontrol of pests, would still remain missing.

Tools for Sustainable Forestry

The economic output of forestry depends on the growth rate, health and resilience of forests which, in turn, depends largely on the local management practices. Forest owners and managers can increase timber production by controlling wood diseases, encouraging biocontrol agents, drain, irrigate, choose between harvesting options, enhance storm and fire resistance, adapt to climate change etc. For such decision making a forester might need a forest health toolbox. The InVEST toolbox contains a managed timber production model, but ignores forest health and resilience issues. Hence, we must seek these functions in other, domain-specific forest management toolkits.

Of the available toolkits, UBC-FM (University of British Columbia Forest Management, Seely et al. 2004) DSS unites a variety of independent models and associated research programs focused on various aspects of forest ecosystem management. That integrated DSS helps to manage forests in a multi-objective context. The system links individual models within a hierarchical structure that facilitates the transfer of data between models through common databases. The resulting toolkit pipelines the ecosystem-based, stand-level forest growth simulator (including non-timber values) FORECAST (Kimmins et al., 1999), the spatially explicit, forest-level harvest scheduling simulator FPS-ATLAS (Nelson, 2003), the landscape and habitat simulator SIMFOR (Daust & Sutherland, 1997) and the CALP (Cavens, 2002) visualization system.

UBC-FM DSS demonstrates well how to pipeline various environmental management issues into one super system. However, as UBC-FM only simulates and visualizes various management scenarios, the toolbox may fail to support practical forest management. Compared to controlled agricultural landscapes, forests hold more diversity, uncertainty, unpredictability and quasi-chaotic behaviours which are challenging for simulation of management effects (Messier & Puettmann, 2011). These intrinsic features of forest management encourage the complementing of a toolbox with more flexible tools. In addition to simulation of scenarios, a forest management toolkit might benefit from e.g. problem articulation tools.

Such flexibility characterizes NED-2 (Nute et al. 2004), a robust, intelligent, goal-driven toolbox that integrates vegetation growth models, wildlife models, silvicultural models, GIS, and visualization tools. NED-2 uses a blackboard architecture and a set of semi-autonomous agents to manage these tools for the user. Users can simulate forest management plans and perform goal analysis. Individual agents use meta-knowledge to set up and run external simulation models, to load rule-based models and perform inference etc. NED-2 has supported management of forest ecological systems in the eastern United States.

In contrast with UBC-FM, NED-2 integrates knowledge bases and can incorporate other tools easily. For instance, the Goal Selection module, a NED-2 knowledge tool, contains rules which enable users to select management goals for timber, wildlife, water, visual quality, and ecology from a pre-defined list. Another knowledge tool in NED-2, Prolog, provides a list of available simulators for silvicultural treatments and establishes default parameters for these treatments. A meta-knowledge base provides a simulation agent with the tables needed to translate data between the NED-2 format and the simulation format.

Unfortunately, none of the above models contain expert systems or other collective EDSSs. Nevertheless, various stakeholders and several experts often participate in strategic decision-making in forest management. Only collaborative process can ensure addressing of all appropriate issues (Fall et al. 2001).

Sturtevant et al. (2007) developed a collaborative modelling approach in sustainable forest management. They applied metamodeling strategy and adaptive management philosophy to facilitate participation of stakeholders, policy makers, and local domain experts in strategic decision-making. However, a computerized meta-model for the application of their concept remains a future challenge.

Tools for the Management of Recreational Sites

Nature recreation includes many different activities: hunting, angling, mushrooming, bird-watching, photography, hiking, mountaineering, rock climbing, walking, running, horseback riding, swimming, boating, skiing, gliding, biking, safari, sunbathing, camping etc. These activities may generate negative environmental impacts such as disturbance or death of wild animals, littering, noise, air pollution, habitat destruction, landscape degradation, soil erosion, destruction of vegetation etc. Hence, management of recreational areas could benefit from domain-specific tools. However, the variation in recreational management situations challenges modellers.

Instead of a toolkit for integrated recreational nature site management, there are now only isolated tools. For instance, the Wilderness Simulation Model (Smith & Krutilla, 1976) predicts relationships between the natural, undisturbed purity of a wilderness and the human influences that affect it.

An envisaged future Recreational Site Management Toolkit might combine RBSim (Geographic Simulation of Wilderness Recreation Behavior; Itami et al., 2003) and SODA (Simulation of Disturbance Activities; Bennett et al., 2009). RBSim simulates, using autonomous agents, the behaviour of human recreators in high use natural environments. RBSIM reveals movement, location and concentration of visitors. In addition to RBSim, a few other agent-based models simulate behaviour of mobile objects such as tourists (Johnson & Sieber, 2010; Macal & North, 2010). However, none of these models simulate tourism-related environmental impacts.

RBSIM could be complemented by the spatially explicit individual-based model, SODA, which calculates the effects of spatial and temporal patterns of anthropogenic disturbance on wildlife. SODA specifically explores repercussions (for example, variations in foraging rate, sleep deprivation, increased energy expenditure and decreased time spent feeding or in contact with young) of ecotourism and other outdoor recreational activities (such as dog-walking, bird watching, mountain-biking, snowmobiling and kayaking) on wildlife.

It seems that either pipelining or toolboxed integration of the above mentioned agent-based models might generate a powerful EDSS which predicts wildlife disturbances as consequences from management decisions such as number of cars and visitors, parking spaces, road and trail widths, capacity of facilities etc. As RBSIM simulates location and concentration of visitors, it might easily match technically with environmental impacts of these visitors, provided by SODA.

However, in addition to the disturbance of wildlife, tourism generates other environmental impacts which remain overlooked in the existing EDSSs. This gap results partly from the extreme variability of management situations, which challenge simulation models but might be removed by introduction of more flexible EDSSs such as reasoning tools. For instance, Cudgen Lake Bayesian Network (Ticehurst et al. 2007) aids sustainable management of small lakes. Compared to arithmetic computations carried out by simulation models, Bayesian networks reason well in low-certainty conditions. These networks work with qualitative data and explicitly consider uncertainty; they enable easy updating and participatory modeling. In recreational management, Bayesian networks facilitate integration of economic, social and environmental variables. These abilities suggest a wide use of Bayesian networks and other qualitative reasoning tools in future recreational EDSSs.

Tools beyond Arithmetic Computations

Most existing tools for the management of local environmental problems address quantitative reasoning (Table 5). They are mostly predictive models which perform arithmetic calculations, analysing the results of various management scenarios. Quantitative reasoning tools, either deterministic or stochastic, require much input information, combined with relatively simple environmental conditions and standardized management situations. At the same time, the availability of more flexible option assessment techniques – such as qualitative reasoning tools, training tools, case-based reasoning tools, etc., remains very limited.

Table 5. The availability of environmental decision support tools for the management of local environmental issues

Tool types	Examples	Availability
Issue definition and criteria setting tools: checklists, dialectic DSSs	Landscape Management Checklist (Lindenmayer et al., 2008); DDSS (Jarupathirun & Zahedi, 2006)	Low
Option generation tools: creative environments	JAIST Nanatsudaki (Wierzbicki & Nakamori, 2007)	Low
Qualitative reasoning tools for option assessment: qualitative models, Bayesian networks, artificial neural networks, environmental ontologies, libraries of qualitative conditional statements	Lake Cudgen Bn (Ticehurst et al. 2007)	Low
Quantitative reasoning tools for option assessment: predictive models, optimization models	DSSAT (Jones et al., 2003)	High
Visualization tools for option assessment	Lenné 3D (Werner et al., 2005)	Moderate
Other reasoning tools for option assessment: training tools, case-based reasoning tools	NATURNET-REDIME (Nuttle & Bouwer, 2009)	Low
Knowledge engineering tools (collective DSSs): expert systems, participatory DSSs,	GEOTOX (Wilson et al., 1986)	Low

Looking decision-making is a sequential process, flowing through issue definition, criteria setting, option generation and option assessment. Most EDSSs nowadays address only the last, option assessment step. The pre-assessment steps remain largely ignored. Identification of this gap leads to the following development suggestions for future EDSS. To address the high variability of management situations, the most practical existing domain-specific tools need integration to multifunctional toolboxes, containing various technologies. The existing toolboxes, in turn, might benefit from the integration to more advanced toolboxes. While most of the existing toolboxes support only option assessment, future development should address also earlier decision-making steps.

CONCLUSIONS

The InVEST project has provided a good integrated framework for the development of a comprehensive ecosystem management toolbox. However, the first version of the toolbox provides little practical decision support. This gap has partly been bridged by some more specialised toolkits.

The existing crop management toolkits cover soil health issues well but remain very limited in wider field health issues such as ecosystems around the fields (grassy field margin etc.) providing biodiversity, biocontrol agents, pollinators and other services. A Sustainable Forest Management Toolkit addresses forest health issues well. However, it has been applied mostly in Canada. Hence, adaption to the European conditions might appear challenging. There is no comprehensive recreational site management toolkit (Figure 11). Core models for such a toolkit might be RBSIM and SODA.

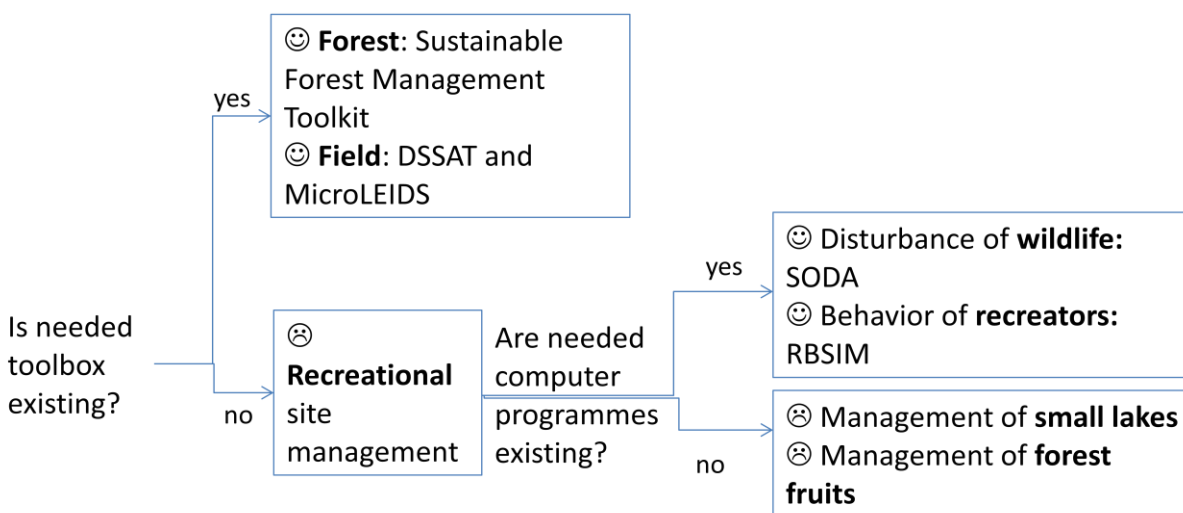


Figure 11. Results of vertical gap search

Considering the need for information for the management of various types of ecosystem services (Chapters 3 and 7), the database provides models about provisioning and supporting services (Table 6). Gaps have been identified in biodiversity, regulating and cultural services.

Table 6. Results of an analysis for thematic gaps.

Ecosystem service type	Information demand	Information supply	Conclusion
Biodiversity	high	low	thematic gap!
Provisioning	low	high	ok
Regulating	medium	low	thematic gap!
Supporting	medium	high	ok
Cultural	medium	low	thematic gap!

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KEY TERMS

Keywords

Ecological Modelling, Ecosystem Services, Environmental Decision Support System, Model of Hierarchical Complexity, Information Gap, Intuitive Reasoning, Metadatabase, Modelling Toolkit