

Design and Implementation of Environmental Information Systems

**Three case studies for managing climate and land-use change
in Forestry and Agriculture**

Dissertation

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Abstract

Environmental Information Systems are Information Systems developed and applied in the environmental domain to handle environmental data and information and to support the management of environmental challenges. Environmental Information Systems do not form an own type of Information Systems. Instead, any type of Information System, e.g. Expert System, Management Information System, Decision Support System, Collaboration System, Spatial Data Infrastructure etc. is an Environmental Information System if it is applied in the environmental domain.

Finding answers to the large environmental challenges such as land-use change, air pollution and climate change, often requires interdisciplinary research, management of large datasets and a transfer of research findings to practical application. Environmental Information Systems can serve as a technical base to support data handling, information extraction, and knowledge transfer as well as identifying knowledge gaps.

According to the design-oriented research approach of business informatics, the present thesis contributes a set of case studies with corresponding IT artifacts to the scientific field of Environmental Information Systems by describing and discussing the design and implementation of two different Environmental Decision Support Systems and a supporting eResearch Infrastructure. The three systems present different new solutions to fill gaps in their field of application regarding the design and implementation of the Environmental Information Systems. A common feature of all of these systems is that they integrate existing knowledge and IT artifacts and combine them to new innovative systems. While the first DSS addresses especially methodological and technical aspects of the coupling of existing models into an integrated simulation system, the second DSS presents a solution of knowledge integration by the consumption of input files. The eResearch Infrastructure was created by the adoption and combination of existing IT artifacts to a new comprehensive collaboration as well as data and information management infrastructure.

The first case study is a Decision Support System for individual use. DSS-WuK is a web-based system offering climate change impact assessments on forests, regarding biotic and abiotic disturbers complemented by an economic evaluation. The key of this DSS is its mastermodel connecting established models describing different climate change impacts and being written in different programming languages. To the best of the author's knowledge, this was the first successful approach in building an integrated simulation system based on established models applicable to whole Germany due to former conceptional and technical issues. The presented solution is adaptable to other systems integrating existing models. An application example of the simulation system to managed forest stands of Norway spruce is presented and discussed.

The second case study is a Decision Support System for group-decision making and par-

ticipatory modeling. BEAST is a Desktop application for specifying and evaluating different scenarios of woody bioenergy production based on Multi-Criteria Decision Analysis. Using this tool, political goals can be assessed in the context of the available biomass potentials of a region and the defined economic as well as ecological framework. Therefore, it supports the development and analysis of regional climate management plans. Beside the scenario-based calculation of biomass potentials of wood from forests and landscape measurements, a main focus of BEAST is to find optimal locations for sitting Short Rotation Coppices (SRC). This end-user-ready standalone application with its high flexibility fills the gap between already existing paper-and-pencil DSS frameworks, simple spreadsheet-based end-user DSS and highly complex scientific bioenergy simulation systems. To the best of the author's knowledge it is the first system that provides a SRC location analysis with a design that complements existing approaches and addresses end-users with a ready-to-use software product that delivers multi-criteria scenario generation and simulation combined with GIS-based processing and output presentation at an intermediate level of detail.

As mentioned, large environmental challenges, such as land-use and climate change, require interdisciplinary research as well as management of large datasets. Therefore, the third case study of this thesis presents an eResearch Infrastructure with tools for information and data management as well as collaboration. This case study shows how to transfer existing software tools to application scenarios in scientific collaboration. For the collaborating researchers in the two research projects it was completely new to use tools such as Wikis, video conference and data management systems. The usage of innovative software tools for collaboration, information and data management based on open standards supports an increased efficiency in the generation of new scientific findings.

The present thesis closes with a description of the lessons learned and suggests aspects for further research.

Zusammenfassung

Umweltinformationssysteme sind Informationssysteme, deren Anwendungsgebiet im Bereich von umweltbezogenen Fragestellungen liegt. Sie kommen zum Einsatz, wenn Umweltdaten und -informationen erhoben, verwaltet und beobachtet werden sowie bei der Lösung von umweltbezogenen Entscheidungsproblemen. Umweltinformationssysteme bilden keinen eigenen Typ von Informationssystemen, stattdessen kann jeder Informationssystemtyp, z.B. Expertensystem, Managementinformationssystem, Entscheidungsunterstützungssystem, Kollaborationssystem, Geodateninfrastruktursystem etc. zu den Umweltinformationssystemen zählen, wenn das entsprechende System für umweltbezogene Fragestellungen eingesetzt wird.

Die Entwicklung von Lösungen für die großen Umweltherausforderungen der heutigen Zeit, wie z.B. Landnutzungsänderungen, Luftverschmutzung und Klimawandel, erfordert zumeist interdisziplinäre Forschung, den Umgang mit großen Datensätzen und den Transfer von wissenschaftlichen Erkenntnissen in die Praxis. Umweltinformationssysteme können dabei als technische Basis für das Datenmanagement, die Informationsextraktion, den Wissenstransfer und die Identifikation von Wissenslücken dienen.

Die vorliegende Arbeit trägt zur Weiterentwicklung des Wissenschaftsgebiets der Umweltinformationssysteme bei, indem in Anlehnung an den gestaltungsorientierten Forschungsansatz der Wirtschaftsinformatik fallstudienbasiert IT-Artefakte entwickelt und diskutiert werden. Zwei Fallstudien beschreiben das Design und die Implementierung von Entscheidungsunterstützungssystemen und eine dritte Fallstudie dokumentiert die Entwicklung einer unterstützenden eResearch-Infrastruktur und deren Komponenten. Die drei Systeme präsentieren verschiedene neue Lösungen, um die bestehenden Lücken hinsichtlich der Konzeption und Implementierung von Umweltinformationssystemen in ihrem jeweiligen Anwendungsbereich zu schließen. Eine gemeinsame Eigenschaft all dieser Systeme ist, dass Sie vorhandenes Wissen und IT-Artefakte integrieren und zu neuen innovativen Systemen kombinieren. Während das erste Entscheidungsunterstützungssystem insbesondere methodische und technische Herausforderungen bezüglich der Kopplung bestehender Modelle in ein integriertes Simulationssystem löst, stellt das zweite Entscheidungsunterstützungssystem eine Lösung der Wissensintegration durch die Einbindung von Inputdateien vor. Die eResearch-Infrastruktur wurde durch die Übertragung und Kombination bestehender IT-Artefakte zu einer umfassenden Kollaborations- sowie Daten- und Informationsmanagement-Infrastruktur geschaffen.

Die erste Fallstudie beschreibt ein Entscheidungsunterstützungssystem für die individuelle Nutzung. DSS-WuK ist ein web-basiertes System zur Folgenabschätzung des Klimawandels für Wälder hinsichtlich biotischer und abiotischer Störungen, ergänzt um eine ökonomische Evaluation. Der Kern dieses Entscheidungsunterstützungssystems ist sein Mastermodell, das

die verschiedenen etablierten Teilmodelle verbindet und den Prozess- und Datenfluss koordiniert. Die Teilmodelle beschreiben die verschiedenen Störungsregime und sind in unterschiedlichen Programmiersprachen implementiert. Nach bestem Wissen des Autors war dies der erste erfolgreiche Ansatz für die Implementierung eines integrierten Simulationssystems, das auf etablierten Modellen basiert und auf ganz Deutschland anwendbar ist. Mit dem hier beschriebenen System konnten die bisherigen konzeptionellen und technischen Hindernisse überwunden werden. Der präsentierte Lösungsansatz kann auf andere Systeme, bei denen existierende Modelle integriert werden müssen, übertragen werden. Ein Anwendungsbeispiel des Simulationssystems auf bewirtschaftete Fichtenbestände wird vorgestellt und besprochen.

Die zweite Fallstudie beschreibt ein Entscheidungsunterstützungssystem für die Nutzung in Gruppenentscheidungsprozessen unter Einsatz partizipativer Modellierung. BEAST ist eine Desktop-Anwendung für die Entwicklung und Evaluation verschiedener Szenarien der Produktion von holziger Biomasse für die energetische Nutzung basierend auf einer multi-kriteriellen Entscheidungsanalyse. Das Werkzeug kann genutzt werden, um politische Ziele der Energiewende hinsichtlich des verfügbaren Biomassepotentials in einer Region vor dem Hintergrund von definierten ökonomischen und ökologischen Rahmenbedingungen zu evaluieren. Es kann für die Entwicklung und Analyse von regionalen Klimamanagementplänen eingesetzt werden. Neben der Potentialberechnung für Waldholz und Landschaftspflegeholz ist die Hauptfunktion von BEAST die Suche nach optimalen Standorten für die Anlage von Kurzumtriebsplantagen. Diese anwendungsreife Standalone-Anwendung mit ihrer hohen Flexibilität schließt die Lücke zwischen bereits bestehenden Papier-und-Stift Entscheidungsunterstützungsrahmenwerken, einfachen tabellenkalkulationsbasierten Endbenutzer-DSS und komplexen wissenschaftlichen Bioenergie-Simulationssystemen. Nach bestem Wissen des Autors ist es das erste Entscheidungsunterstützungssystem zur Standortanalyse für Kurzumtriebsplantagen mit einem Design, das bestehende Ansätze ergänzt anstatt sie zu ersetzen und Endnutzer mit einem gebrauchsfertigen Softwareprodukt versorgt, welches multikriterielle Szenariogenerierung und -simulation mit GIS-basierter Prozessierung und Ergebnispräsentation auf einer mittleren Detailebene kombiniert.

Wie erwähnt, erfordern die großen Umweltherausforderungen interdisziplinäre Forschungen sowie den Umgang mit großen Datensätzen. Hier setzt die dritte Fallstudie der vorliegenden Arbeit an, indem die Architektur und Entwicklung einer unterstützenden eResearch-Infrastruktur mit Komponenten für das Informations- und Datenmanagement sowie Kollaborationswerkzeugen präsentiert und diskutiert werden. Diese Fallstudie zeigt, wie bestehende Software-Tools auf Anwendungsszenarien der wissenschaftlichen Zusammenarbeit übertragen werden können. Für die Wissenschaftler in den beiden Forschungsprojekten war die Nutzung von Tools wie Wikis, Videokonferenz- und Datenmanagementsystemen neu. Die Nutzung von Softwaretools für die Kollaboration sowie das Informations- und Datenmanagement auf Basis offener Standards ermöglichte eine erhöhte Effizienz bei der Generierung neuer wissenschaftlicher Erkenntnisse.

Einer kritischen Auseinandersetzung mit den gewonnenen Erkenntnissen schließt die vorliegende Arbeit ab und zeigt Vorschläge für weitere Forschungsfragen auf.

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Introduction

I.1. Data, Information, and Knowledge

As defined by Oxford Dictionary [Wehmeier and Ashby, 2000] information are 'facts provided or learned about something or someone', data is 'information that is stored by a computer' and knowledge is 'the information, understanding and skills that you gain through education or experience'. In scientific literature a second, more hierarchical separated definition of the terms exists. In this definition data is seen as non-random symbols (syntax) that represent values of attributes or events. Information is generated by transforming data in a way that makes sense to receiving person (context) [Lapiedra Alcamí et al., 2012]. Finally, a network of information mixed with beliefs and experiences expresses knowledge [Hopfenbeck, 2000, see also Figure I.1]. However, from an information technology perspective information can still be data with additional meta-data describing the context. Therefore, as this thesis is located in the field of applied sciences, the term information used throughout this thesis includes data in this meaning.

Thus, information is a working basis for science as well as for management. Information is able to modify existing probability judgments and, therefore, is important in decision making processes [Arentzen and Winter, 1997].

Since the invention and widespread of information technology (IT) an unprecedented increase and availability of information have taken place [Cukier, 2010]. Sensor-based automated measurements, computer-based simulations, and the connection of information pools forming information networks made professional information handling necessary.

I.2. Information Systems

This requirement of information handling led to the development of Information Systems. However, several meanings of the term 'Information System' exist. A listing of various definitions can be found, for example, in Alter [2008]. Carvalho [1999] identified four different categories of definitions:

- IS1: Organizations (autonomous systems) whose business (purpose) is to provide information to their clients.

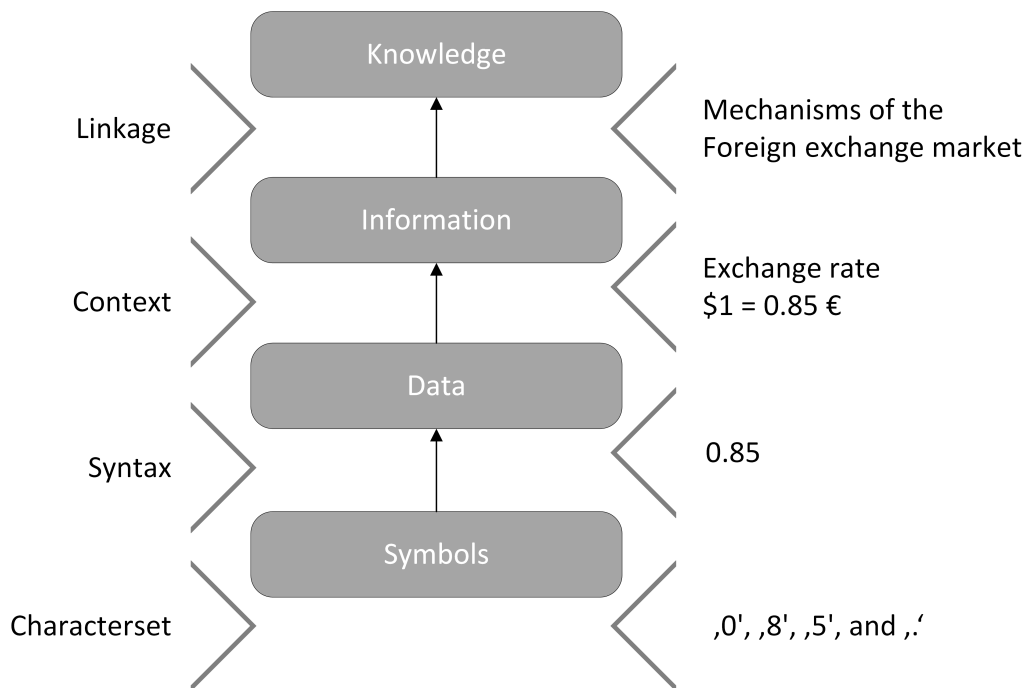


Figure I.1.: Hierarchy between symbol, data, information, and knowledge after Rehäuser and Krcmar [1998].

- IS2: A subsystem that exists in any system that is capable of governing itself (autonomous system). The information system (IS2) assures the communication between the managerial and operational subsystems of an organization – that is its purpose. When this communication is asynchronous, a memory to store the messages is necessary. IS2 includes such memory.
- IS3: Any combination of active objects (processors) that deal only with symbolic objects (information) and whose agents are computers or computer-based devices – a computer-based system.
- IS4: Any combination of active objects (processors) that deal only with symbolic objects (information).

Throughout this thesis the definition by Aalst and Stahl [2011] is used: „a software system to capture, transmit, store, retrieve, manipulate, or display information, thereby supporting people, organizations, or other software systems“. It is an IT-centered view on 'Information Systems' and fits into type 3 (IS3) of Carvalho [1999]. Examples of this Information System type comprise data processing systems, management information systems, decision support systems, data mining systems etc. [Carvalho, 1999].

This broader class of 'Information Systems' can be separated into transaction processing applications and systems addressing administration/management [Davis, 2000]. The latter one is in focus of this thesis. Typical types of this class of 'Information Systems' are shortly described in the following. Then, the interrelations of these types are shown and the term 'Environmental Information Systems' is introduced.

I.2.1. Management Information Systems

The development of Management Information Systems (MIS) goes back to the 1960s when the consolidation of formerly separated transaction processing functions using various incompatible hard- and software systems into a centralized processing system was in focus due to technological advances [Hirschheim and Klein, 2011]. Nevertheless, a general accepted definition of the term Management Information System in literature is missing [Lucey, 2004]. A very wide definition comes from Kroenke et al. [2013] by summarizing MIS as an Information System that help businesses to achieve their goals and objectives. Lucey [2004] defined a MIS as „a system to convert data from internal and external sources into information and to communicate that information, in an appropriate form, to managers at all levels in all functions to enable them to make timely and effective decisions for planning, directing and controlling the activities for which they are responsible“. MIS should be systems targeting the needs of all levels of management, i.e., operational, tactical, and strategic [Lapiedra Alcamí et al., 2012]. However, in practice classical MIS were inflexible, missed appropriate database models and systems, and did not help making decisions of unexpected problems. Therefore, they have not been adopted by top management and have been often deemed to be failed in reaching their goals [Müller and Lenz, 2013]. However, the term is still in use due to its unspecific definition. Additionally, as stated by Davis [2000] the term MIS is sometimes used interchangeable with IS.

I.2.2. Executive Information Systems

Executive Information Systems (EIS) have been developed as successors of early-days classical Management Information Systems (MIS) and are predecessors of Business Intelligence (BI) Systems (see below). Whereas MIS should provide all available information in a global system, EIS instead provide a partial system presenting only relevant information in aggregated form, especially addressing the top management [Lucey, 2004]. EIS are tailored to control activities in daily business and figure out problems and opportunities [Lapiedra Alcamí et al., 2012]. They provide functions to analyze various data sources and create reports with comfortable graphical user interfaces and are, in contrast to Decision Support Systems (in a narrow definition, see below), not fixed to a special decision problem and the evaluation of different alternatives to this problem [Rieger, 1992]. Specific applications of EIS in the environmental domain are rather rare. Examples of EIS applications in the broader environmental domain are a EIS of weather forecast and its impact on the retail industry [Fox et al., 1994] and the human resource monitoring EIS of the U.S. Farm Service Agency [U.S. Dep. of Agriculture, 2011].

I.2.3. Expert Systems

Expert Systems (ES) emulate human cognitive skills of problem-solving within a limited domain by using Artificial Intelligence (AI) techniques [Jackson, 1990]. They belong to the so called knowledge-based systems and are applied to complex, semi- or unstructured problems [Macharzina, 1999]. ES have been developed since the 1970s for various topics [Wong and Monaco, 1995, Jones, 2009]. Such a system typically consists of a knowledge base, an inference engine that uses the knowledge base to generate new knowledge by applying heuristic inference rules, an explanation component that delivers insights into the inference process, a dialog component to communicate with the user, and a knowledge

acquisition component for entering expert knowledge [Kurbel, 1992, Jackson, 1990, Puppe, 2012]. They are self-learning systems that replace the decision making expert in application scenarios where experts are rare or the decision problems are too complex for a human expert due to the amount of alternatives or incomplete data [Wöhe and Döring, 2000]. Various types of ES have been developed including web-based ES as well as multi-agent systems [Liao, 2005, Duan et al., 2005, Grove, 2000]. A recent review by Wagner [2017] showed the on-going relevance of ES. ES have also been developed for the management of natural resources [Bremdal, 1997].

1.2.4. Business Intelligence Systems

Gartner [2017] described BI as „an umbrella term that includes the applications, infrastructure and tools, and best practices that enable access to and analysis of information to improve and optimize decisions and performance“. BI-Systems are tailored to provide information of the internal state and the external environment to the management [Müller and Lenz, 2013]. A BI-System is the IT solution for this BI process. BI-Systems are not fixed to a specific problem but typically provide a configurable graphical user interface with data analysis and visualization tools [Sherman, 2014]. The backbone of the data analysis and visualization BI-System is a data warehouse or data marts and the data integration process using extraction, transformation and loading (ETL) tools [Elbashir et al., 2008]. BI-Systems provide functions such as configurable dashboards and reports as well as online analytical processing (OLAP) and data mining capabilities [Chen et al., 2012, Müller and Lenz, 2013]. In business context BI-Systems are sometimes seen as the successors of Decision Support Systems (see below) and Executive Information Systems (see above) arising in 1990s [Petrini and Pozzebon, 2009]. In contrast, Skyrius et al. [2013] defined BI-Systems as general purpose systems for constant monitoring in daily business whereas DSS as systems for solving a specific problem. BI-Systems typically complement Enterprise-Resource-Planning (ERP) Systems. They are used also for environmental monitoring [Petrini and Pozzebon, 2009].

1.2.5. Big Data Analytics

Currently, Big Data Analytics (BDA) is one of the most popular topics in Information technology in different domains [Kumar, 2016, Bughin et al., 2010, Akter et al., 2016]. This trend results from the fast growing amount of available data by, e.g., sensor-generation and Internet of Things in various domains from government over business to health organizations [Chen et al., 2012]. Many companies started to collect and store as many data as possible from various sources to derive patterns and future trends [Stange and Funk, 2016]. Whereas traditional data collection was based on carefully selected experimental design, big data is the collection of any type of data - often in real-time - in any form (structured and unstructured) with often low information density which requires new forms of data models, storage and analysis [Pyne et al., 2016]. New database types, like the Nosql databases, has been developed to be used for Big Data [Moniruzzaman and Hossain, 2013]. Big Data is sometimes characterized by the so-called five V's: volume (amount of data), velocity (rate of data generation), variety (type of data - structured, unstructured, semi-structured), veracity (abnormality in data), and value (intrinsic value that the data may possess and that can be uncovered by analytics) [Kumar, 2016, Marr, 2015]. In the beginnings only the first three V's have been used to characterize Big Data which proved to be imperfect [Mayer-

Schönberger and Cukier, 2013]. When spatial location of the data is of relevance it is called Geospatial Big Data [Olasz et al., 2017].

Sometimes, BDA is summarized under Business Intelligence but extends the analytical toolset compared to classical data analytics by techniques for text, audio, video, mobile, and social media analytics as well as has a stronger focus on predictive analytics [Gandomi and Haider, 2015, Chen et al., 2012]. BDA differs also in speed, scale, and complexity to traditional BI [Minelli et al., 2013]. In agriculture the application of BDA is already widely discussed under the topic 'Smart Farming' [Kempenaar et al., 2016]. It is expected that the use of sensor networks, robots, and artificial intelligence will have large impact on farming and the whole food supply chain in future [Wolfert et al., 2017]. An overview of recent applications of BDA in agriculture can be found in Kamilaris et al. [2017]. A recent special issue of Journal of Cleaner Production was dedicated to Big Data approaches for natural resource management and human health [Song et al., 2017].

I.2.6. Geographical Information Systems

A Geographic Information System (GIS) is a specialized Information System to capture, manipulate, visualize, combine, query, model, and analyze spatial data, i.e., data containing a location that matters [Bonham-Carter, 1994]. In 1964, Canadian federal agencies responsible for environment and agriculture began operating the Canada Geographic Information System (CGIS) [Tomlinson, 1987]. CGIS handled the Canadian Land Inventory mapping providing data about agriculture, forestry, wildlife, fisheries, recreation, and land use and is known as the first operational GIS [Kemp, 2008]. A second origin goes back to the application of GIS technology for analyzing the US population census in the late 1960s which was later combined with CGIS resulting in the first multi-function GIS created by the Harvard Laboratory for Computer Graphics and Spatial Analysis [Maliene et al., 2011]. Thus, in contrast to MIS, EIS, and BI-Systems which have their origins and main application areas in classical business management context, GIS is a sub-type of Information Systems with a strong multidisciplinary character and influences from various disciplines [Blaschke and Merschdorf, 2014, Coppock and Rhind, 1991]. When the widespread of GIS applications started in the 1980s the first adopters have been forestry companies and natural resource agencies [Longley et al., 2010]. Nowadays, Geographic Information Systems are widely-used tools for data processing in various disciplines where location is of importance, such as marketing, military, public infrastructure planning, as well as environmental and natural resource management [Bernhardsen, 2002, Pick, 2004, Hess et al., 2004]. As GIS is mostly used for decision support, these systems are also called Spatial Decision Support Systems (sDSS, see below) [Keenan, 2002]. Furthermore, Spatial Data Repositories (SDR) and Spatial Data Infrastructures (SDI) are often associated with GIS [Pick, 2004, Longley et al., 2010]. SDRs and SDIs are introduced below.

I.2.7. Decision Support Systems

The term Decision Support System (DSS) is widely used for very different kinds of systems. This resulted in various assumptions about what a DSS is and makes distinguishment to other types of Information Systems rather fuzzy [Sprague, 1980, Eom et al., 1998, Turban et al., 2004, Averweg, 2008a].

In general, a DSS is intended to assist a non-random activity of selection-decision among

multiple alternatives [Holsapple, 2008]. Therefore, the focus of a DSS is the decision whereas the focus of a MIS is on information [Sprague, 1980]. Power [2002a] summarized three major characteristics of DSS based on the work of Alter [1980]:

1. are designed specifically to facilitate decision processes,
2. should support rather than automate decision making, and
3. should be able to respond quickly to the changing needs of decision makers.

The term Decision Support System was introduced by Gorry and Scott-Morton [1971] when they distinguished Structured Decision Systems (SDS) from Decision Support Systems in business context. They categorized the classical Management Information Systems (see above) as SDS because they only support solving so-called structured problems, where the decision-making activities in the phases intelligence, design, and choice are well-known and structured. In turn, DSS are tailored to assist in so-called semi- and, sometimes, unstructured problems. For this type of problems the decision-maker does not know all aspects of the decision task. Therefore, models and data manipulation tools are used to support the decision-making process [Averweg, 2008b].

Although research and early developments of DSS go back to the 1970s [Sprague, 1980], the widespread of DSS development and application in the business domain started in 1980s in conjunction with the widespread of personal computers and spreadsheet software [Arnott and Pervan, 2005]. In the course of the widespread of the World-Wide-Web/Internet in the mid 1990s, this technique has also been used to develop so-called web-based DSS where Web-browsers are typically used as thin-clients in a Client-Server-architecture [Bhargava et al., 2007, Power and Sharda, 2007]. Comprehensive reviews of the history of DSS can be found at Power [2008a] and Averweg [2008a].

As described by Turban et al. [2004] a DSS typically consists of at least the following three technical components: data-management subsystem, model-management subsystem and a user interface subsystem. It can be further extended by a knowledge-based management subsystem for artificial intelligence functionality. Based on these components, Power [2002b] introduced a typology of DSS as an extension of the work of Alter [1980], depending on the core component characterizing a specific DSS. Therefore, he distinguished communications-driven, data-driven, document-driven, knowledge-driven, and model-driven DSS. Nevertheless, hybrid systems can occur, when a DSS is driven by more than one major component.

Communications-driven DSS are systems that provide communication and collaboration techniques to foster cooperation and information exchange within groups working on a common task. They include tools like groupware, videoconferencing and bullet boards [Kulkarni et al., 2007].

Document-driven DSS are systems that support document-based requests and approvals where documents are a central part of a decision making process. Documents, information or tasks are passed from one participant to another or process steps are automated. They are realized in Business Process Management (BPM)/Workflow software [Kulkarni et al., 2007].

Knowledge-driven DSS are characterized by the ability to recommend actions based on artificial intelligence. As Power [2002a] used a rather wide definition of DSS he summarized Expert Systems (see above) as knowledge-driven DSS in contrast to others, e.g., Ford [1985], who clearly distinguished between DSS and ES.

Data-driven DSS are database-centered management reporting systems that provide access and manipulation functions for large databases of structured data. In contrast to other definitions of DSS, Power [2002a] summarized Executive Information Systems (EIS) and Business Intelligence Systems (BI) under this category. Furthermore, Spatial Decision Support Systems are often also assigned to the data-driven DSS [Power, 2008b]. Those sDSS have mainly developed independently from classical DSS in the context of Geographic Information Systems (see above). They are used to include spatial information into the decision problem and are, therefore, mostly driven by accessing and manipulating spatial data [Keenan, 2002].

Model-driven DSS are systems that provide access and manipulation functions for models, like statistical, optimization or simulation models including agent-based models, where users of the DSS can modify model parameters and/or input data [Power and Sharda, 2007].

The classification by Power [2002b] is widely used, however, other authors suggested other types. For example, Holsapple and Whinston [1996] distinguished text-oriented, database-oriented, spreadsheet-oriented, (fixed and flexible) solver-oriented, and rule-oriented DSS. Hackathorn and Keen [1981] classified DSS into personal, group and organizational support systems.

Classical DSS in business context comprise, for example, the SCHUFA DSS for supporting the decision about the creditability of customers [Schufa, 2017]. Another example is a DSS presented by Ghodsypour and O'Brien [1998] for supplier selection and optimal purchasing. A further example by Wai et al. [2016] is a DSS tailored for production scheduling based on data analysis of ERP-System. For a collection of DSS examples from various application domains see, for example, Papathanasiou et al. [2016].

A collection of DSS applications in ecosystem management, agriculture, food and environment can be found, for example, in Manos et al. [2010] and Mowrer [1997].

I.2.8. Data Repositories/Infrastructures

Following Heery and Anderson [2005] a Repository is a digital collection with the following characteristics:

- Content is deposited in a repository, either by the content creator, owner or third party.
- The repository architecture manages content as well as metadata.
- The repository offers a minimum set of basic services, e.g., put, get, search, and access control.
- The repository must be sustainable and trusted, well-supported and well-managed.

Repositories can have various target user scopes from a single research project (individual), over a university in its whole (institutional) to national-wide and global, or from divisions (individual) , over a company in its whole (institutional) to all companies of a sector etc. [Davis, 2000]. Therefore, Baker and Yarmey [2009] differentiated local and remote repositories, with local repositories being close to the data origin with a focus on data management whereas remote repositories have their focus on collection management with long-term storage. Repositories are typically available via the Intra- or Internet and can be operated as an internal system with restricted access or as public systems [Marco, 2000, Stenson, 2016]. Many Data Repositories have been established in academia as so-called

Research Data Repositories for the management and preservation of scientific data [DANS, 2010].

Examples for individual and institutional Research Data Repositories are TR32DB project database [Curdts and Hoffmeister, 2015] and BEFdata platform used by BEF-China as well as FunDivEurope projects [Nadrowski et al., 2013]. Moreover, various public repositories have been established, like DRIADE/Dryad [Greenberg et al., 2009, 2007] and OpenAIRE/OpenAIREplus [Manghi et al., 2012]. Several funding organizations require a Research Data Management including data management and preservation in Research Data Repositories, e.g., DFG [DFG, 2015]. Also initiatives on governmental and political level, such as by the OECD [OECD, 2007] and the European Commission [European Commission, 2016, 2012, Commission of the European Communities, 2009], have been started to foster RDM and Research Data Repository uptake. Furthermore, registries for public research data repositories have been established. For example, the German Research Foundation (DFG) funds an initiative to develop a global registry of research data repositories (re3data) covering various academic disciplines [Pampel et al., 2013].

When multiple repositories implement interfaces for the exchange of data/information with each other they build up a data/information infrastructure (additional organizational and legal agreements could be necessary). An infrastructure works by dynamically harvesting metadata from connected repositories.

If repositories' content is used for decision-making it may be assigned to the category of Decision Support Systems (when a broad definition is used, see above).

Spatial Data Repositories/Infrastructures

A special case of Data Repositories are the Spatial Data Repositories (SDR) for storage of collections of spatial data [Cockcroft, 2004, Béjar et al., 2009]. SDRs are typically used as a data source for Geographic Information Systems and, therefore, evolved in the context of GIS [Pick, 2004]. SDRs complemented by a user interface, a spatial data service, a catalogue service, and a GIS for data maintenance forming the technical backbone of a Spatial Data Infrastructure (SDI) [Steiniger and Hunter, 2012].

A SDI is a „collection of technologies, policies and institutional arrangements that facilitate the availability of and access to spatial data“ [Nebert, 2004]. Technical interoperability of the systems of a SDI enables harvesting of data from one repository by another within the SDI. The Open Geospatial Consortium (OGC) has a leading role in interoperability specification for SDI functions and GIS in general [OGC, 2017].

The development of SDIs was mainly influenced by the public sector. A milestone was the call for the development of a National Spatial Data Infrastructure (NSDI) in the USA in 1994 [Executive Order 12906, Clinton, 1994]. In 2007, the European Union fostered the establishment of a pan-European SDI with the so-called INSPIRE Directive by creating interoperability of national SDIs [Directive 2007/2/EC, EU, 2007]. A main target of the Directive was the assistance of policy-making with impact on the environment by making spatial data and data services available and compatible [EU, 2007]. Following the Directive a SDI in this sense means spatial data sets, metadata, spatial data services, network services, and technologies, agreements on sharing, access and use as well as coordination and monitoring mechanisms, processes, and procedures [EU, 2007].

Several institutions contributed to the implementation of INSPIRE including, for example, forest, agriculture, and fishery research institutions like the von Thünen Institute with its

Thünen-SDI [Thünen, 2017]. Nash and Kofahl [2006] presented how specialized SDIs could provide an Information System component in precision farming.

I.2.9. Synthesis and Environmental Information Systems

The typology uncovered that the different types of Information Systems are strongly interrelated and not always clearly distinguishable. The interdependency of the different IS types are visualized in a concept map in Figure I.2.

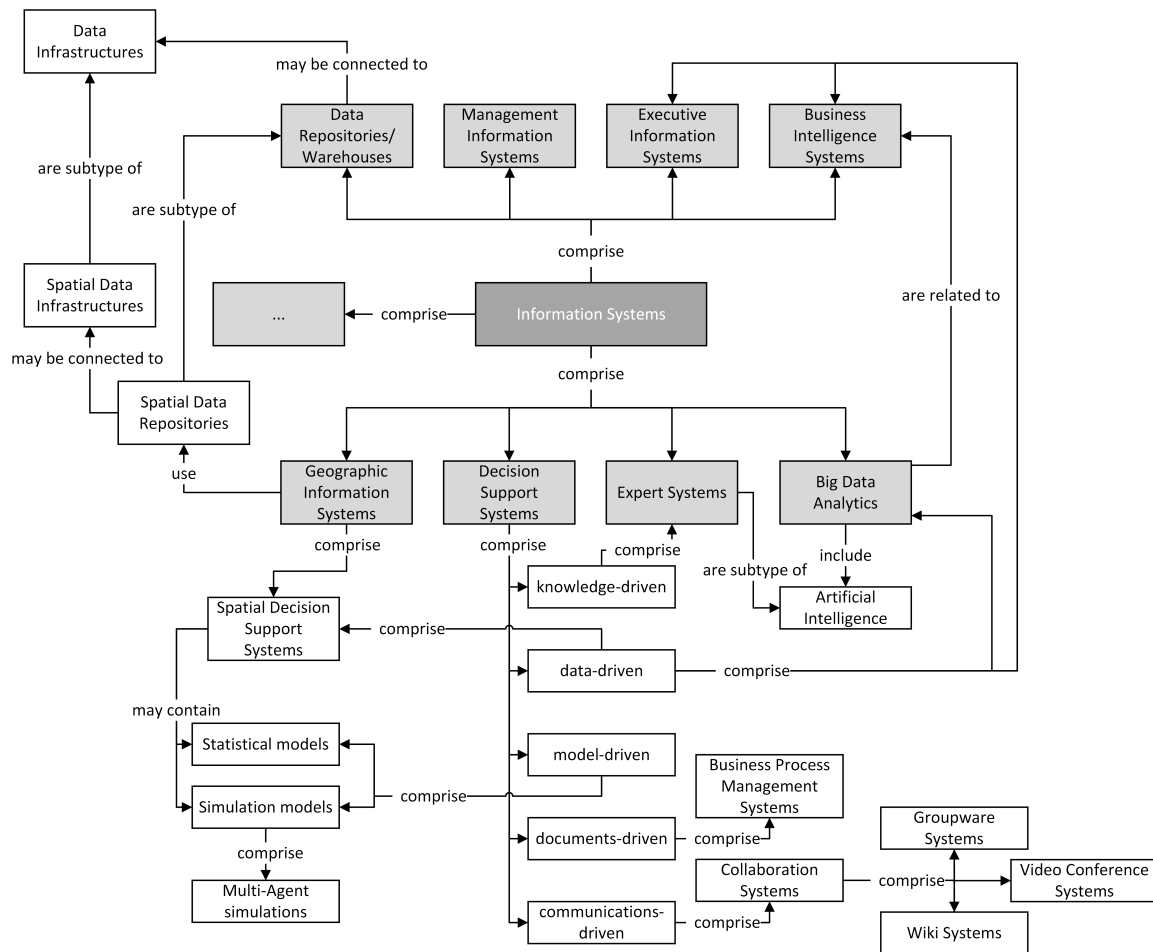


Figure I.2.: Concept map of Information Systems.

Independent from the functional type, Information Systems are developed for various application domains as depicted in Figure I.3. Thus, Environmental Information Systems (EnvIS) are not an own type of Information Systems with unique functionality and do not appear in the concept map. Instead, an Environmental Information System is an IS applied to the environmental domain such as biodiversity protection, ecosystem sustainability, natural resource management, climate change adaption, environmental hazards management for which the availability of adequate data and information is essential [European Commission, 2015]. Therefore, EnvIS is an umbrella term potentially covering all types of Information Systems depending on the application domain. Figure I.4 visualizes this fact.

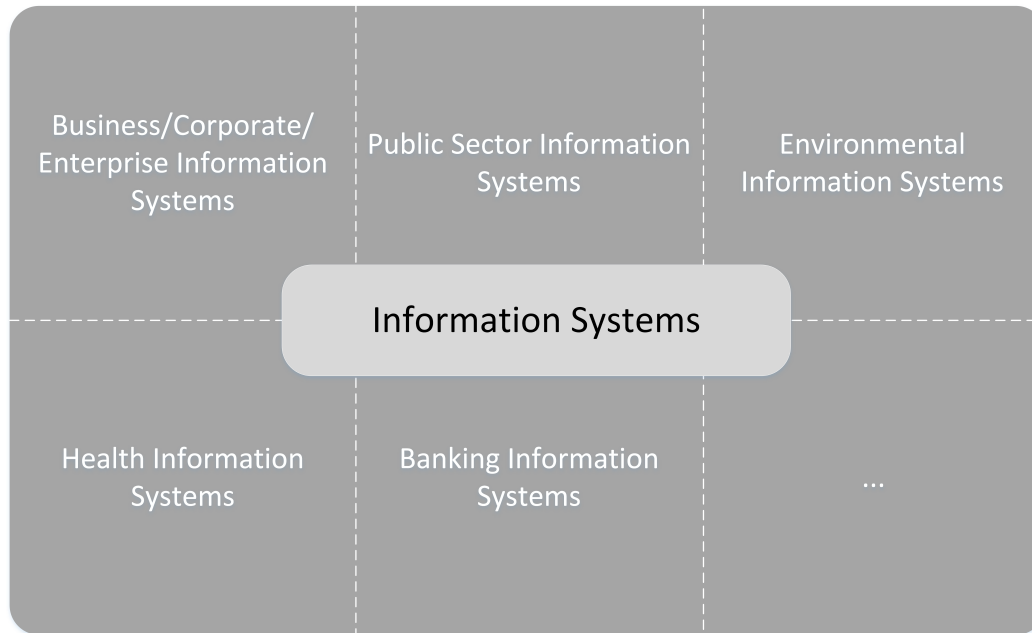


Figure I.3.: Example application domains of Information Systems, which often overlaps.

Formal definitions of EnvIS are given, for example, by Günther [1998] who defined that they are Information Systems that „are concerned with the management of data about the soil, the water, the air, and the species in the world around us“ and Usländer [2010], who said that EnvIS „are Information Systems that deal with geospatial information and services with a reference to a location on the Earth“. EnvIS are applied in various sectors such as industry, science, and public administrations for monitoring and control, computational evaluation, analysis, planning, decision support etc. [Page and Rautenstrauch, 2000, Frysinger, 2012].

Sometimes the term Environmental Information System is used explicitly but in many cases it is not. Therefore, a lot of systems exist that are not labeled as EnvIS although they would be in scope. Examples for the explicit usage of the term are the so-called Shared Environmental Information Systems which interoperate with each other and share their data and information to gain new insights into the state and dynamic of environmental systems [European Commission, 2008]. On the European governmental level the European Environment Information and Observation Network (EIONET) with its subsystems such as EIONET-Soil was established [European Environment Agency, 2016, Panagos et al., 2014]. Another example are the so-called Corporate Environmental Information Systems (CEnvIS) for monitoring and reporting environmental sustainability in business operations, for instance carbon footprints of products and business operations, and corresponding industrial standardization of environmental management, such as the ISO 14000 standard family [ISO, 2009], requiring (Corporate) Environmental Information Systems [Möller, 2010, Hamilton and Baker, 2003, Arndt, 1997]. Jamous et al. [2012] gave examples of Corporate Environmental Information Systems for monitoring and reporting the carbon footprint. Volkswagen AG uses

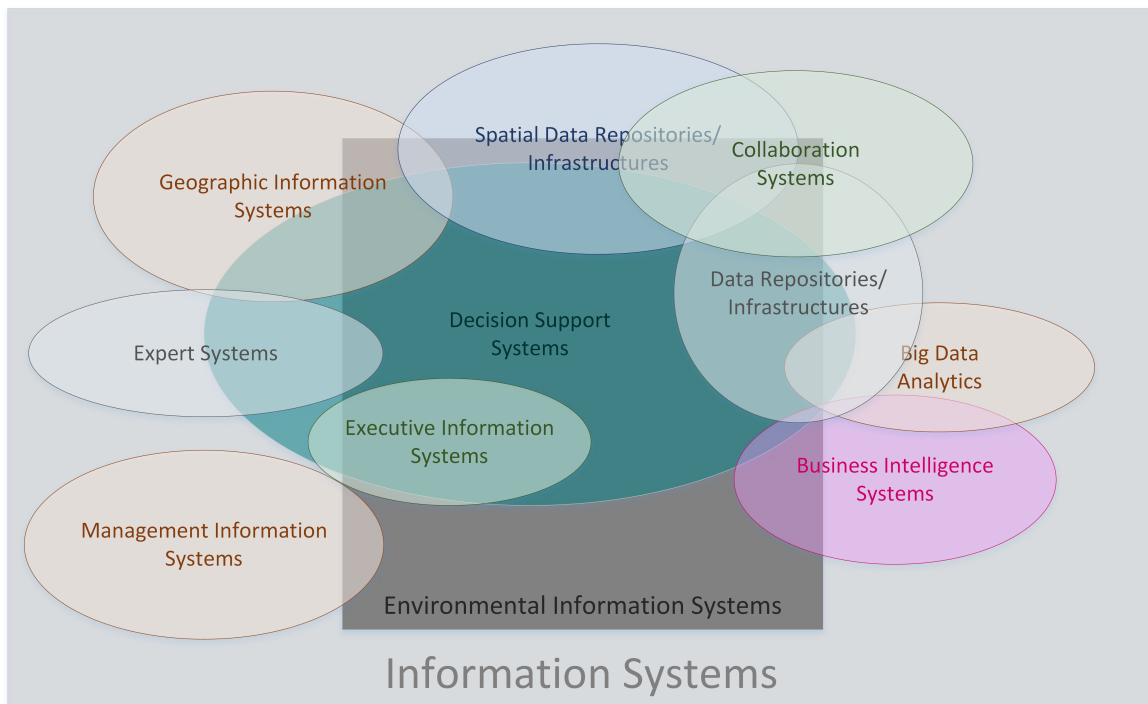


Figure I.4.: Schematic visualization of the relationship between IS, EnvIS, and the different types of IS. Overlapping areas represent interrelations, e.g., Spatial Data Repositories/Infrastructures (light blue colored bubble) are (partly) related to Geographic Information Systems (brown colored bubble), both belong partly to Decision Support Systems (dark green colored bubble), which belong to Environmental Information Systems (dark gray colored box). All of these systems belong to Information Systems (light gray colored box).

an internal Environmental Information System in material flow analysis [Volkswagen AG, 2017].

Sometimes a prefix 'Environmental' is assigned to the types of IS to clarify their application to the environmental domain. An often used subtype is that of Environmental Decision Support Systems (EnvDSS), which is described in more detail in the following excursion, as the systems presented in this thesis can be partly assigned to this subtype.

Environmental Decision Support Systems Decision-making in natural resource and environmental management is often characterized by handling complex and dynamic system mechanisms and conflicting goals regarding, e.g., ecology, economy, politics, and society [Liu and Taylor, 2002]. Therefore, the application of Multi-Criteria Decision Analysis (MCDA) techniques for mediating trade-offs of conflicting goals [e.g., Herath and Prato, 2017, Huang et al., 2011, Hayashi, 2000, Nijkamp and Rietveld, 1986] as well as the development and application of various kinds of models for system understanding and prediction is commonly used in Environmental Sciences [Wainwright and Mulligan, 2013]. Environmental models are an essential tool for understanding, representing, and communicating impacts of management decisions [Jakeman et al., 2008].

The need for environmental models and decision-support increased since the end of the last century to find new policy objectives and implementation options to face the environmental and social changes such as climate change, forest dieback, species extinction, and environmental pollution [McIntosh et al., 2011].

To provide decision-makers access to those models as well as the necessary data and information EnvDSS have been developed. Additionally, McIntosh et al. [2011] highlighted the aspect of transparency of rational decision-making because EnvDSS results are reproducible by anyone and the strength and robustness of scenario results can be tested.

Following Rizzoli and Young [1997] EnvDSS are software systems that provide access to databases and integrated models of various aspects developed for the environmental domain. This development meant that scientific research was extended from pure analysis towards software development for decision-/policy-making [Matthies et al., 2007].

Although a lot of systems published as EnvDSS are single models of only one aspect of an environmental decision problem, Poch et al. [2004] as well as Rizzoli and Young [1997] underpinned the strength of EnvDSS in the combination and integration of multiple models and different tools to handle the complexity of environmental decision problems. Therefore, Matthies et al. [2007] summarized EnvDSS as systems „of various coupled environmental models, databases and assessment tools, which are integrated under a graphical user interface (GUI), often realized by using spatial data management functionalities provided by geographical information systems (GIS)“.

Poch et al. [2004] reported that EnvDSS have been applied to a wide range of tasks from data storage, over monitoring, control planning, remediation, management, decision analysis to communication. Also the range of environmental problems for which EnvDSS have been developed is large. It includes, for example, biomass logistics [e.g., Frombo et al., 2009], river-basin management [e.g., Berlekamp et al., 2007], waste water management [e.g., Massei et al., 2014], irrigation management [e.g., Navarro-Hellín et al., 2016, Rinaldi and He, 2014], sustainable farm management [e.g., Rao et al., 2007], and forest management [e.g., Reynolds and Hessburg, 2005, Lexer et al., 2005].

Listings and reviews of EnvDSS can be found, for example, in:

- McIntosh et al. [2011] - reviewed 19 EnvDSS from various domains,
- Newman et al. [2017] - reviewed 101 EnvDSS from natural hazards domain,
- Poch et al. [2017] - reviewed four EnvDSS from waste water management domain,
- Mowrer [1997] - evaluated 24 EnvDSS from ecosystem management domain,
- Rauscher [1999] - reviewed 33 EnvDSS from forest management domain, and
- Packalen et al. [2013] - reviewed 62 EnvDSS from forest management domain.

Especially in the forest management domain many scientific books and papers have been published about the development and usage of EnvDSS, e.g., Nobre et al. [2016], Hansen and Nagel [2014], Vacik and Lexer [2014], Segura et al. [2014], Kangas et al. [2008], Reynolds et al. [2008], Reynolds [2005], Lexer and Brooks [2005], Rauscher et al. [2005], Kangas and Kangas [2002].

I.3. Motivation

According to the design-oriented research approach from business informatics [e.g., Hevner et al., 2004], the present thesis aims to show how Environmental Information Systems can be designed and implemented to be applied to current topics of environmental management and research to support decision making in practice, uncover further research needs and support corresponding research. The focus is on technical and methodological aspects regarding the design and implementation of EnvIS by means of case studies and the development of corresponding IT artifacts. Three case studies are used to present how EnvIS can be designed and implemented for (1) climate impact assessment and decision support on forests, (2) decision support for woody bioenergy production, and (3) collaboration and data management for data-intensive and interdisciplinary research projects, as being necessary for the development of the first two case studies. The case studies should serve as best practice examples for different kinds of EnvIS.

The first case study presents a data-intensive, model-driven web-based and spatial Decision Support System. This work has been part of the joint research project 'Decision Support System Wald und Klimawandel - Anpassungsstrategien für eine nachhaltige Waldbewirtschaftung unter sich wandelnden Klimabedingungen (DSS-WuK)' funded by the Federal Ministry of Education and Research (Grant No. 01LS05117) in the time frame 2007 - 2010.

The second case study presents a spatial Decision Support System for individual and participative group modelling of bioenergy production from dendromass. This work has been part of the joint research project 'BEST: Bioenergie-Regionen stärken - neue Systemlösungen im Spannungsfeld ökologischer, ökonomischer und sozialer Anforderungen' funded also by the Federal Ministry of Education and Research (Grant No. 033L033) in the time frame 2010 - 2014.

In contrast to the first two case studies, the third's case study target audience are not practitioners and policy-makers but researchers. The development of integrated EnvIS by researchers often requires interdisciplinary teams, collaborative work at different locations and with large amounts of shared datasets. Information System technologies can support those team work with collaboration systems as well as data repositories. These topics are part of the third case study: eResearch Infrastructures developed in the context of the named joint research projects.

I.4. Structure of the Thesis

Based on the three case studies this thesis is structured in three main parts beside this general introduction and an integrative discussion at the end.

Chapter II presents the development and application of the Decision Support System for impact assessment of climate change on forests. This chapter includes three research papers:

- JC Thiele, RS Nuske, B Ahrends, J Saborowski [2009]. Entwicklung eines Entscheidungsunterstützungssystems für die Waldbewirtschaftung unter sich ändernden Klimabedingungen. In: M Mahammadzadeh, H Biebeler, H Bardt: Klimaschutz und Anpassung an die Klimafolgen. Institut der deutschen Wirtschaft Köln Medien GmbH. Köln. pp. 303–310.
- JC Thiele and RS Nuske [2016]. Design and Implementation of a Web-Based Decision Support System for Climate Change Impact Assessment on Forests. *Forstarchiv* 87: 11-23.
- JC Thiele, RS Nuske, B Ahrends, O Panferov, M Albert, K Staupendahl, U Junghans, M Jansen, J Saborowski [2017]. Climate Change Impact Assessment - A Simulation Experiment with Norway Spruce for a Forest District in Central Europe. *Ecological Modelling* 346: 30–47.

Chapter III introduces the Decision Support System for participatory modeling of woody bioenergy production from forest wood, wood from outside forests, as well as wood from short rotation coppices, with a focus on the spatial location selection of Short Rotation Coppices. This chapter consists of two research papers:

- JC Thiele and G Busch [2015]. A Decision Support System to Link Stakeholder Perception with Regional Renewable Energy Goals for Woody Biomass. In: D Butler Manning, A Bemann, M Bredemeier, N Lamersdorf and C Ammer (Eds). *Bioenergy from Dendromass for the Sustainable Development of Rural Areas*. Wiley. pp 433–446.
- JC Thiele [accepted]. Participative Dendromass Bioenergy Modeling in Regional Dialogs with the Open-Source BEAST System. *Journal of Agricultural Informatics* 9 (3).

Chapter IV presents information, data, and collaboration systems as parts of an eResearch Infrastructure. As presented above, those systems are related to DSS and (Spatial) Data Repositories/Infrastructures and are used here to support the research projects. This chapter includes the following four papers:

- JC Thiele [submitted]. eResearch – Digital Service Infrastructures for Collaboration, Information, and Data Management in Joint Research Projects in Ecology – An Example. *International Journal of E-Collaboration*.
- JC Thiele and RS Nuske [2008]. Mit Hilfe von Wikis vom Wissen aller Mitarbeiter profitieren. *AFZ/Der Wald* 18: 974–976.
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CHAPTER II

Decision Support System Wald und Klimawandel

SECTION II.1

Entwicklung eines Entscheidungsunterstützungssystems für die Waldbewirtschaftung unter sich ändernden Klimabedingungen

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Authorship

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- Joachim Saborowski supervised the writing of the manuscript.

II.1.1. Zusammenfassung

Die sich abzeichnenden globalen Umweltveränderungen werden zukünftig die Waldökosysteme Umweltfaktoren aussetzen, die sich in ihrer Kombination und Dynamik von denen der Vergangenheit unterscheiden. Das Ausmaß und die Geschwindigkeit dieses Wandels sowie die Wechselwirkungen zwischen den Änderungen werden vielerorts die natürlichen Anpassungsmechanismen der Wälder überfordern. Da diese zukünftigen Risiken aus den bisherigen Erfahrungen nur schwer ableitbar sind, wurden im 'Decision Support System Wald und Klimawandel (DSS-WuK)' Modelle und Methoden entwickelt und verknüpft, mit der die zu erwartenden standörtlichen Veränderungen für die nächsten 100 Jahre abgebildet und die Stressoren Wind, Trockenheit und biotische Schaderreger abgeschätzt werden können. Darüber hinaus ermöglicht das webbasierte Entscheidungsunterstützungssystem die Einschätzung der waldwachstumskundlichen Veränderungen mit Hilfe eines klima- und standortsensitiven Wachstumssimulators sowie eine ökonomische Bewertung der Risiken und Wachstumsveränderung. Da für die Akzeptanz eines solchen Systems die Zielgruppenorientierung und Benutzerfreundlichkeit von herausragender Bedeutung sind, wurden bei der Implementierung von Beginn an potentielle Nutzer in den Entwicklungsprozess eingebunden.

II.1.2. Einleitung

Durch die globalen Umweltveränderungen werden unsere Waldökosysteme in den nächsten Jahrzehnten Umweltfaktoren ausgesetzt sein, die sich in ihrer Kombination und Dynamik grundsätzlich von denen der Vergangenheit unterscheiden. Für Wälder in Deutschland sind vor allem der Temperaturanstieg, die veränderten Niederschlagsverteilungen sowie Witterungsextreme mit Starkregen, Stürmen und Trockenperioden [Solomon et al., 2007] von Bedeutung. Diese Faktoren werden in Kombination mit dem Anstieg der Kohlendioxid- und Ozongehalte der Luft, der anhaltenden Bodenversauerung sowie der Nährstoffverarmung und Stickstoffsättigung der Böden auf den Wald wirken.

Wie sich die Kombination warmer und trockener Perioden auf die Wälder Mitteleuropas auswirkt, konnte bereits im Sommer 2003 beispielhaft für verschiedene Standorte ermitteln werden. Damals wurden eine erhebliche Einschränkung der Assimilationsleistung bei reduzierten Wassergehalten [Granier et al., 2007] und damit einhergehend Zuwachsverluste beobachtet. Dobbertin et al. [2007] zeigten zudem, dass auch in den Jahren nach Trockenperioden noch eine erhöhte Anfälligkeit des Baumbestandes gegenüber Schaderregern besteht. Weitere Wechselwirkungen aus sich wandelnden klimatischen Randbedingungen ergeben sich für das Sturmwurfrisiko (aufgrund feuchterer Winter) und durch eine veränderte stoffliche Ernährungssituation der Wälder.

Folglich lässt sich das Erfahrungswissen der Förster nicht mehr unmittelbar in die Zukunft übertragen. Vor dem Hintergrund von Produktionszeiträumen von über 100 Jahren sind die langfristige Planung und die sorgfältige Baumartenwahl für die Bewirtschaftung des Waldes jedoch unerlässlich.

Um in der strategischen Planung die Umweltfaktoren in ihren neuen Kombinationen und Wirkungen auf der Ebene der Waldökosysteme zu berücksichtigen, müssen modellgestützte Verfahren eingesetzt werden.

II.1.3. Zielgruppe und Anforderungen

Das Entscheidungsunterstützungssystem „DSS-WuK – Decision Support System Wald und Klimawandel“ richtet sich an die Entscheidungsträger auf der forstbetrieblichen Ebene mit entsprechendem forstlichen Sachverstand. Dabei soll das System die Zielgruppe vor allem bei der Bewertung unterstützen, wie gut sich verschiedene Baumarten für die Erreichung der betrieblichen Ziele eignen. In sogenannten Nutzerforen wurde mit potenziellen Nutzern (Praxispartner) herausgearbeitet, welche Themen das DSS-WuK behandeln soll.

Die Teilnehmer bewegte einerseits die Frage, welche Dimension der Klimawandel in ihren Regionen sowie für bestimmte Bestandestypen aufweisen wird und wie dies die Anbauwürdigkeit der einzelnen Baumarten verändert. Andererseits bestand der Wunsch, die eigene Situation im Vergleich zu anderen Regionen beurteilen zu können, um zu erkennen, ob man sich in einer Region hoher Gefährdung befindet. Des Weiteren war den potenziellen Nutzern wichtig, dass das Entscheidungsunterstützungssystem leicht zu bedienen ist und die verwendeten Methoden und Modelle in dem System dokumentiert sind.

II.1.4. Entscheidungsunterstützungssystem Wald und Klimawandel

Bei einem Entscheidungsunterstützungssystem handelt es sich um ein Werkzeug, das bei der Erarbeitung und Bewertung von Handlungsalternativen auf der Grundlage von Umweltdaten Hilfestellungen bietet. Anwendungsgebiete solcher Decision-Support-Systeme (DSS) sind Entscheidungen auf der Ebene des Managements, die zumeist schlecht strukturiert sind. Auch in Forstbetrieben haben Decision-Support-Systeme in den letzten Jahren vermehrt Einzug gehalten [zum Beispiel Vacik and Lexer, 2001].

Aus den oben genannten Anforderungen der Zielgruppe leiten sich unmittelbar die Anforderungen an das zu entwickelnde DSS ab. Das System soll den forstlichen Entscheidungsträgern helfen, die Folgen des Klimawandels hinsichtlich der Anbauwürdigkeit verschiedener Baumarten zu beurteilen.

Um die vielfältigen Anforderungen zu erfüllen, besteht das DSS-WuK aus mehreren Bereichen. Im ersten Bereich findet der Nutzer vorprozessierte bundesweite thematische Karten zum Beispiel zur Niederschlags- und Temperaturveränderung der verwendeten Klimaszenarien. Im zweiten Bereich (siehe Teilmodell 1 in Abb. II.1) kann der Nutzer regional differenzierte Ergebnisse (bestehend aus biotischen und abiotischen Risiken, der Wuchsleistung und der ökonomischen Bewertung) in einer Auflösung von 20 mal 20 Kilometern für einen idealisierten Bestand abrufen. Im Bericht werden die Hauptbaumarten Eiche (*Quercus spec.*), Buche (*Fagus sylvatica*), Fichte (*Picea abies*), Douglasie (*Pseudotsuga menziesii*) und Kiefer (*Pinus sylvestris*) vergleichend dargestellt. Die Ausgabe erfolgt für vier Perioden in den Jahren von 1980 bis 2100. Im dritten Bereich (siehe Teilmodell 2 in Abb. II.1) besteht für den Nutzer die Möglichkeit, für jeweils eine Baumart eine solche Beurteilung in einer höheren räumlichen Auflösung anzufordern. Ergänzt werden diese drei Bereiche durch ein Hintergrundinformationssystem, das dem Nutzer sowohl allgemeine Informationen zum Klimawandel und zu den Szenarien als auch detaillierte Beschreibungen der eingesetzten Modelle zur Verfügung stellt.

Modellkonzept

Kern des DSS-WuK ist das Mastermodell, welches die verschiedenen Submodelle zu einem Gesamtsystem verbindet. Auf der linken Seite der Abbildung II.1 ist der Ablauf des Teil-

modells 1 zu sehen. Dieses beruht weitgehend auf vorprozessierten Daten in der räumlichen Auflösung des regionalen Klimamodells CLM (Climate Local Model). Mit diesem System läßt sich die Anbauwürdigkeit der fünf Hauptbaumarten in der räumlichen Auflösung der CLM-Daten in kurzer Rechenzeit vergleichend darstellen. Auf der rechten Seite der Abbildung II.1 befindet sich das Teilmodell 2, welches dynamisch-gekoppelt arbeitet.

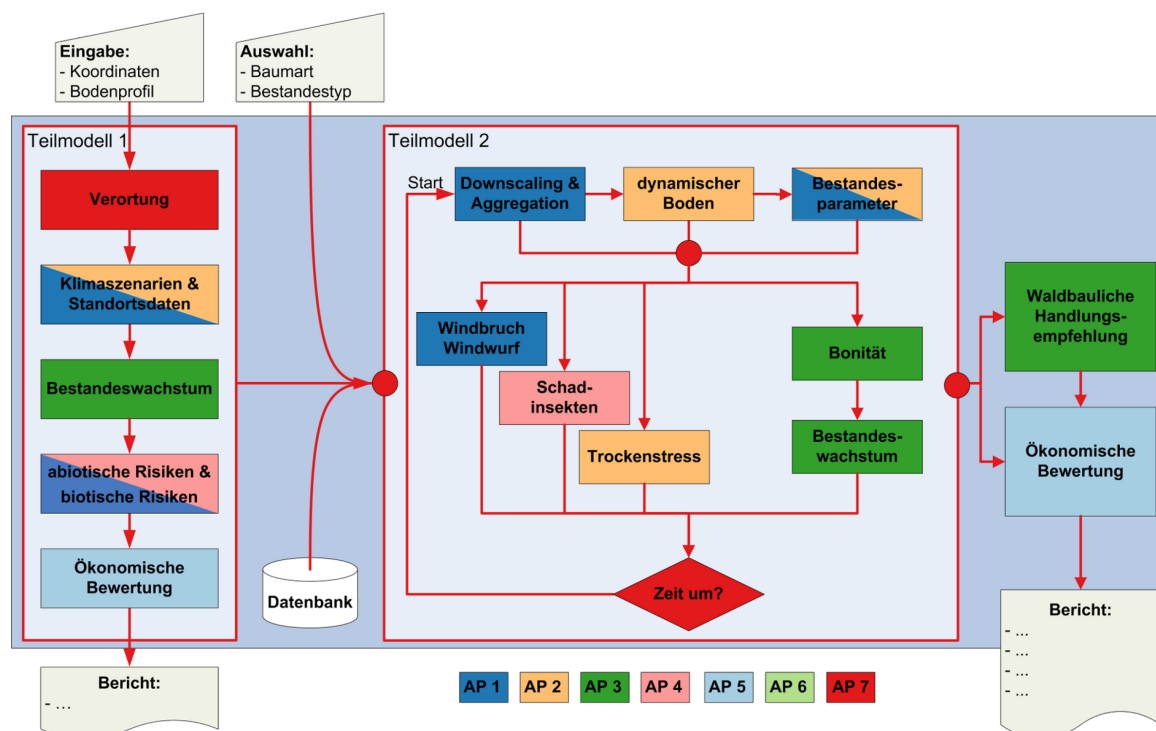


Abbildung II.1.: Mastermodell.

Im Teilmodell 1 werden die Submodelle sukzessiv abgearbeitet, nachdem der Nutzer seine Anfrage unter Eingabe seiner Koordinaten (Längen- und Breitengrad) und der Auswahl eines Bodenprofils gestartet hat. Mit Hilfe der Koordinaten werden zunächst Klimadaten sowie Standortdaten der entsprechenden Rasterzelle aus der Datenbank geladen. Mit diesen Daten bestimmt das Bonitätsmodell die Wuchsleistung der Baumarten auf dem Standort. Nachdem die vorprozessierten abiotischen (Windbruch/Windwurf, Trockenstress) und biotischen Risikowerte aus der Datenbank gelesen wurden, erfolgt die Berechnung eines mittleren Deckungsbeitrags mithilfe eines Betriebsklassenmodells.

Startet der Nutzer hingegen das Teilmodell 2, welches Ergebnisse für jeweils nur eine Baumart liefert, sind zusätzliche Benutzereingaben zum Bestandesalter notwendig, da hier mit einem dynamischen (allerdings von Risiken unbeeinflussten) Bestand gerechnet wird. Zudem findet hier ein Downscaling der Klimadaten auf eine höhere Auflösung statt. Die Submodelle werden nun iterativ in einer Schleife abgearbeitet. Das koordinierende Zeitintervall der Schleife beträgt zehn Jahre. In diesem Rhythmus wächst der betrachtete Bestand. Die Submodelle rechnen den nächsten Zeitschritt mit aktualisierten Eingangsdaten. Klima-, Bestandes- und Bodenparameter bilden die Eingangsgrößen für die Risikomodelle und das Bonitätsmodell, welches wiederum das Bestandeswachstum beeinflusst und so eine klimasensitive Fortschreibung des Bestandes ermöglicht.

Im Anschluss an die Schleife werden waldbauliche Handlungsempfehlungen in Form von 3D-Ökogrammen ausgegeben, welche die Optimal- und die Grenzbereiche der Baumarten visualisieren. Zudem integriert eine ökonomische Bewertung des Gesamtrisikos die Einzelrisiken in einer ökonomischen Kennzahl. Aufgrund der aufwendigen Simulationen ist hier eine schnelle Ausgabe nicht möglich.

Submodelle

Im Folgenden werden die in Abbildung II.1 dargestellten und oben eingeführten Submodelle näher beschrieben.

Downscaling der Klimavariablen Für Europa wurden die globalen Klimaprojektionen mit dem Regionalmodell CLM auf eine höhere räumliche Auflösung skaliert. Die CLM-Daten haben eine horizontale Auflösung von 0,165 Grad beziehungsweise 0,2 Grad und stellen die Grundlage des DSS-WuK dar. Um die verschiedenen Risiken auf Ebene eines Waldbestandes modellieren zu können, werden die meteorologischen Variablen (Windgeschwindigkeit, Temperatur, Niederschlag und andere) unter Berücksichtigung der kleinskaligen Variationen der Topografie und Vegetation mithilfe des SVAT-Regio-Modells [Olchev et al., 2009] herunterskaliert. Im klimazwei-Projekt DSS-WuK werden die Läufe 1 und 2 der Emissions-szenarien A1B und B1 verwendet.

Dynamisches Standortmodell Grundlage für die regionale, flächendifferenzierte Abschätzung des Trockenstresses von Wäldern ist die Modellierung des Bestandeswasserhaushalts. Hydraulische Bodeneigenschaften werden über Leitprofile aus vorliegenden Kartenwerken, beispielsweise der Bodenübersichtskarte (BÜK) 1:1 Million für Waldstandorte oder Standortskarten, zugeordnet. Über Schwellenwerte der Xylemleitfähigkeit, die quantitative Angaben zur Einschränkung der Wasserversorgung der Baumkrone durch Embolien liefern, und deren Zusammenhang mit dem Matrixpotenzial wurden kritische Bodenwasserpoteztiale im Bereich der unteren Hauptwurzelzone für einzelne Hauptbaumarten definiert. Diese kritischen Bodenwasserpoteztiale werden herangezogen, um Schädwirkungen einer Trockenperiode auf die verschiedenen Baumarten abzuschätzen. Als Grundlage für die dynamische Modellierung der Stickstoffeinträge dienen die Depositionskarten des Umweltbundesamts.

Windschadensrisiko Zur Abschätzung von Windschäden werden drei Submodelle in einem Wind-Boden-Baum-Modell gekoppelt. Zur Beschreibung des Winds wird ein 3D-Modell der atmosphärischen Grenzschicht verwendet. Es beschreibt die Dynamik der atmosphärischen Grenzschicht unter Berücksichtigung der Geländehöhe und der Vegetationsbedeckung in hoher zeitlicher und räumlicher Auflösung. Das Windmodul liefert den Winddruck auf Bäume in Waldbeständen in Abhängigkeit von der Geländeposition. Zur Berechnung der Eintrittswahrscheinlichkeit von Sturmschäden unter bekanntem Windstress sind zusätzlich Informationen zu den Bestandes- und Baumeigenschaften sowie zum Boden notwendig. Die Kombination dieser Angaben mit Restriktionen zur Durchwurzelung aufgrund von begrenzter Gründigkeit oder Grund- und Staunässe sowie mit zusätzlichen bestandesstrukturellen Informationen erlaubt eine qualifizierte Schätzung der Bestandesstabilität.

Waldschutzrisiken durch biotische Schaderreger Es werden nur diejenigen Schaderreger im Modell abgebildet, die für die jeweilige Baumart ein hohes Schadenpotenzial besitzen. Von besonderer Bedeutung sind Schädlinge der Fichte und der Kiefer, da bei diesen Baumarten der wirtschaftliche Erfolg stark durch die Schädlinge beeinflusst werden kann. Der Buchdrucker (*Ips typographus*) ist eine große Risikokomponente in einem Fichtenbetrieb, da dieser Schädling von der Klimaerwärmung erheblich profitieren wird. Das Modell PHENIPS [Baier et al., 2007] beschreibt die Entwicklung des Buchdruckers anhand der täglichen Luft- und Stammtemperatur sowie der Strahlung. PHENIPS wurde um ein Fichtenschadmodell erweitert, welches in Abhängigkeit von Bestandesparametern und Trockenheit den Anteil ausfallender Holzmasse an der Gesamtmasse des Bestandes berechnet. Für die Kiefer sind mehrere Insektenarten relevant: Kiefernspinner (*Dendrolymus pini*), Kiefernspanner (*Bupalus piniarius*), Forleule (*Panolis flammea*) und Nonne (*Lymantria monacha*). Die Vermehrung dieser Arten wird durch steigende Durchschnittstemperaturen und sinkende Sommerniederschläge verstärkt. Alle diese Arten neigen zu Massenvermehrungen und haben in der Vergangenheit zum Absterben ganzer Bestände geführt.

Waldwachstum (Standort-Leistungs-Bezug) Herkömmliche Bonitierungssysteme unterstellen eine Konstanz der Standortfaktoren, die aber bereits seit mehreren Jahrzehnten nicht mehr gegeben ist. Als Konsequenz musste daher für die Modellierung des Standort-Leistungs-Bezugs ein Bonitierungssystem angewendet werden, das die Dynamik der Standortfaktoren hinreichend abbildet. Auf Grundlage ertragskundlicher Daten von Betriebsinventuren, der Bundeswaldinventur, zahlreicher klimatischer Faktoren (zum Beispiel Temperatur, Niederschlag, potenzielle Evapotranspiration) und standörtlicher Faktoren (zum Beispiel nutzbare Feldkapazität, Nährstoffversorgung, Stickstoffdeposition) wurden für die Baumarten Standort-Leistungs-Modelle parametrisiert. Durch die Anwendung der Modelle können die Optimal-, die Potenz- und die Grenzbereiche der jeweiligen Baumarten identifiziert werden. Für die anderen Submodelle können durch die Koppelung des Standort-Leistungs-Modells mit dem Waldwachstumssimulator BWINPro der Wachstumsgang eines Bestandes klimasensitiv modelliert und damit Bestandesparameter berechnet werden.

Ökonomische Bewertung In diesem Submodell findet eine ökonomische Bewertung der zuvor ermittelten Klimaeinflüsse mithilfe der Abbildung risikobeeinflusster Zahlungsströme statt. Hierzu dienen dimensionsabhängige Erlös- und Kostenfunktionen, jeweils für reguläre und kalamitätsbedingte Holzernten. Der Risikoeinfluss wird dabei durch die Anpassung einer Überlebensfunktion an die ermittelten Ausfallwahrscheinlichkeiten in einen Flächenausfall überführt. Der gewählte Ansatz erlaubt es, dabei nach Baumarten, Schadenereignissen und Ernteverfahren zu differenzieren.

Modellimplementierung und technische Umsetzung

Da sich in neueren Entscheidungsunterstützungssystemen, um die Benutzer- und Bedienerfreundlichkeit zu erhöhen, der Einsatz von webbasierten Benutzerschnittstellen bewährt hat, wurde auch das DSS-WuK als Webanwendung entwickelt (Abbildung II.2). Besonders vor dem Hintergrund von leistungsschwachen Computern in den Forstbetrieben ist die Auslagerung der rechenintensiven Arbeiten auf einen leistungsstarken Server sinnvoll. Für die Entwicklung der Webapplikation wurde ein bewährtes Webframework (Django) eingesetzt,

welches vor allem auf die zügige Entwicklung von Webapplikationen mit Datenbankanbindungen ausgerichtet ist. Innerhalb dieses Frameworks wurde die Model-Engine umgesetzt, welche die Implementierung des Mastermodells (vgl. Abbildung II.1) darstellt. Die Model-Engine ist sowohl für die Zugriffe auf die Datenbank als auch für die Koordination der Submodelle und die Zusammenstellung der Ergebnisse für den Bericht zuständig. Besonders die Koordination der Datenflüsse zwischen den Submodellen erwies sich als sehr aufwendig, da zum Beispiel viele der Klimadaten in täglicher Auflösung verarbeitet werden. Zudem lagen die Submodelle in verschiedenen Programmiersprachen vor. Darum mussten Schnittstellen geschaffen werden, über die der direkte Zugriff auf die jeweilige Sprache aus der Model-Engine heraus möglich ist.

Für die Darstellung der Übersichtskarten sowie für die Koordinatenauswahl wurde eine Web-GIS-Architektur eingerichtet. Diese besteht aus einem UMN-MapServer, der die Auslieferung der Karten und Legenden an den Webserver (hier Apache 2) als Web-Map-Service (WMS) gemäß dem Open Geospatial Consortium (OGC) übernimmt. Für die Visualisierung (Web-Mapping) fand die JavaScript-Bibliothek OpenLayers Verwendung. Zur Darstellung von Basiskarten wurde der Kartendienst GoogleMaps in OpenLayers eingebunden.

DSS - WuK
Decision Support System - Wald und Klimawandel

Startseite Übersichtskarten Baumartenbeurteilung Hintergründe Kontakt

» Unterstützung bei Entscheidungen
Das «Decision Support System - Wald und Klima» unterstützt Sie bei der Wahl einer Baumart vor dem Hintergrund sich wandelnden Klimas. Das System bietet Ihnen hierfür Informationen auf verschiedenen Ebenen an.

» Übersichtskarten
Einen ersten Eindruck der regionalen Unterschiede des Klimawandels und seiner Auswirkungen auf den Wald können Sie hier gewinnen. Karten der Temperatur- und Niederschlagsänderung beider Klimaszenarien als auch ausgewählter Risiken wurden vorbereitet und stehen in einem Web-GIS als **interaktive Karten** bereit.

» Baumartenbeurteilung
Das System beurteilt die fünf Hauptbaumarten hinsichtlich des Zuwachses, des Windwurfs-, Trockenstress- und biotischen Risikos. Das Risiko kann für eine Koordinate Ihrer Wahl abgefragt werden. Die Beurteilung erfolgt dabei für einen Zeitraum bis zum Jahre 2100, unterteilt in drei Perioden. Es werden die **Klimaszenarien** (B1 und A1B) bei der **Baumartenbeurteilung** berücksichtigt.

» Hintergrundinformationen
Im **Hintergrundinformationssystem** bekommen Sie Auskunft zum Klimawandel allgemein und zu den erwarteten Auswirkungen auf den Wald. Darüber hinaus sind die verwendeten Eingangsdaten sowie den eingesetzten Modellen ausführlich dokumentiert.

Hintergründe
[Institutionen](#)
[Klimamodelle](#)
[Risikobeurteilung](#)
[Modelle](#)

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Abbildung II.2.: Startseite des Prototypen.

II.1.5. Benutzerintegration und Wissenstransfer

Für die Akzeptanz einer Software sind die Zielgruppenorientierung und die Benutzerfreundlichkeit von herausragender Bedeutung. Daher waren potenziellen Nutzer von Beginn an in

den Entwicklungsprozess des Entscheidungsunterstützungssystems DSS-WuK eingebunden. Zu diesem Zweck wurden diverse Testversionen des Systems erstellt, die jeweils als Diskussionsgrundlage dienten und deren Weiterentwicklung unter Berücksichtigung der Vorschläge der Praxispartner letztendlich in der Endversion mündeten. Neben der benutzerorientierten Systementwicklung wurden im Rahmen des Projekts DSS-WuK Strategien erarbeitet, mit denen der Wissenstransfer optimiert werden kann. Hierzu wurden neben schriftlichen Befragungen von potenziellen Nutzern mehrere Informationsforen mit Stakeholdern aus dem Politikfeld Wald und Klima durchgeführt.

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SECTION II.2

Design and Implementation of a Web-Based Decision Support System for Climate Change Impact Assessment on Forests

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Authorship

- Robert S. Nuske supported the design and implementation of the data model, the model coupling in R and the writing of the manuscript.

II.2.1. Abstract

Climate change has altered and further will change the environmental conditions for many sectors. Whereas annual cropping systems can be adapted yearly, decisions in forest management usually have long-lasting effects. Depending on the region and tree species rotation periods range between 80 and 180 years in Central Europe. Therefore, today's tree species selection should also take into account the impacts of climate change in the future.

Although many attempts have been made to understand single aspects of climate change impacts on forests, the available knowledge has to be conflated into an integrated assessment to support decision making. A comprehensive system comprising different impact models and an economic assessment suitable for Central European forests and driven by high-resolution temporal- and spatial data is currently missing.

We present a conceptual design and a reference implementation of a Decision Support System (DSS) tailored to assess climate change impacts on German forests. To provide a high ease-of-use, the system was implemented as a web application and offers information for single stands on-demand as well as interactive maps and preprocessed assessments on a coarser level for entire Germany. To create such a complex, integrated system from legacy models written in different programming languages the interfaces had to be developed carefully. The key of this DSS is its building blocks: established models describing different climate change impacts. Since the DSS is a very modular system, it is easy to replace submodels and to adapt it to other study areas, forest systems or research questions if suitable parameterized models and input data are available. The presented technical solution is adaptable to other systems integrating existing models and the source code is available.

II.2.2. Introduction

Climate change has altered and further will change the environmental conditions for many sectors [IPCC, 2013, Munich Re, 2011]. Whereas annual cropping systems can be adapted yearly to those changes, decisions in forest management will have long-lasting effects. Depending on the region and tree species, rotation periods in Central Europe mostly range between 80 and 180 years [Lower Saxony Ministry of Food, Agriculture and Consumer Protection, 2014]. Therefore, today's tree species selection should take into account the climate change impacts in the future [Lindner et al., 2014, Yousefpour and Hanewinkel, 2015].

Impacts of the projected climate change on forests are manifold. In Germany, for example, rising temperatures, changing precipitation patterns and increasing frequency of extreme events are projected [Spekat et al., 2007, Becker et al., 2008, Jacob et al., 2008]. These are likely to change growth conditions of forests having positive as well as negative effects [Bolte et al., 2009a, Lindner et al., 2010]. However, the projected changes will differ temporally and spatially [Enke et al., 2005, Spekat et al., 2007]. Thus, choosing a tree species, rotation time, and forest treatment solely based on past experiences may become inadequate in the light of new combinations and dynamics of environmental factors [Kirilenko and Sedjo, 2007, Jansen et al., 2008].

Several methods have been developed to evaluate the impact of climate change on Central European forests. For example, Kölling [2007] adapted the method of (bio-) climatic envelope modelling [e.g., Box, 1981, Huntley et al., 1995] to tree species in Germany using the factors yearly mean temperature and annual precipitation. A similar approach was

pursued by Asche [2009, 2008] who modeled climate change impacts on German forests by empirical ecograms. Climate change was in this case described by a constant temperature increase and relative changes of precipitation to project length of vegetation period, water balance, and nutrient availability. Since climate change does not happen from one moment to the next but is a non-monotone process, it can be important to use high temporal resolution climate data time series at least for some impacts. For example, a single extreme drought year can be limiting to some tree species [Allen, 2010] which cannot be detected by a single point in time or longtime average considerations only.

Several models describing single impacts have been developed. For example, Blennow et al. [2010] assessed wind damages of Swedish forests and Panferov et al. [2009] of a forest stand in Germany, Carvalho et al. [2011] projected forest fire danger in Portugal, Murdock et al. [2013] examined the risk of insects outbreaks in a changing climate in British Columbia and Berec et al. [2013] for Czech Republic, Gustafson and Sturtevant [2013] modeled drought stress mortality in USA, and Coops et al. [2010] evaluated climate change impact on productivity in British Columbia as well as Albert and Schmidt [2010] in Lower Saxony, Germany.

Although all these attempts are important to understand single aspects of climate change impacting forests, at the end this knowledge has to be combined into an integrated assessment to support decision making. To the best of our knowledge, a comprehensive system comprising different impact models and an economic assessment suitable for Central European forests driven by high-resolution temporal and spatial data is currently missing. Merely conceptual considerations have been presented several years ago by Lindner et al. [2002]. Decision Support Systems (DSS) are important tools able to fill this gap [e.g., Wenkel et al., 2013]. Following the definition of Sprague [1980], DSS are usually employed for complex decision making problems of upper level managers where models are combined with data. They are flexible and adaptable, but at the same time the access to the system for non-computer-expert users is easy. Therefore, DSS are ideal platforms for transferring knowledge from science into practice and have been already applied to forest management problems [e.g., Reynolds, 2005, Packalen et al., 2013, Vacik et al., 2013]. DSS can integrate a wide range of data and models into a single system. They are, thus, well suited to link existing models of different aspects of climate change impact driven by high-resolution climate projection data [Lindner et al., 2002].

In this article we present the design and a reference implementation of a DSS tailored to assess climate change impacts on German forests. The idea of linking established models representing different aspects to an integrated DSS can be adapted to other forest systems and other study areas if suitable parameterized models and input data are available. The focus of this article is neither on the selection of submodels nor the simulation results. Such descriptions can be found in Jansen et al. [2008], Thiele et al. [2009] and Thiele et al. [2010]. Instead, we describe an approach to integrate existing models written in different programming languages to an integrated system. Therefore, the structure of the article is adapted to this task and starts with a presentation of the scope, development and concept of the DSS including the master model that links and coordinates the different submodels and the required data. This is followed by a description of the reference implementation of the DSS. Finally we close with discussion and outlook.

II.2.3. Scope, development and concept of DSS

The Decision Support System “forest and climate change” (German: “Wald und Klimawandel”) was developed in the context of a joint research project funded by the German Federal Ministry for Education and Research. The funding measure imposed strict requirements regarding climate projections (see implementation section below) and integration of practitioners. The resulting tool had to be useable for forest managers and consultants. Thus, the DSS should be easy to install, intuitive to use and must answer the right questions in a way easy to understand. Since the topic of climate change impact assessment is extremely complex the presentation of results needs to be as simple as possible. A high level of transparency regarding data, models, and uncertainties of the system should be achieved so that user do not consider it a “black box”. However, to interpret the results in their full extent expert knowledge of forests will still be required.

To comply with these requirements we installed a “stakeholder process” with representatives of forest practitioners from state and private forests as well as chambers and nature conservation organizations. In biannual meetings we gave approximately ten stakeholders the possibility to test development versions on provided notebooks. Three dummy versions (without real results) and two prototypes have been presented. During the process we discussed what information such a DSS should provide and which system design would be most usable. The stakeholders commented in oral discussions as well as on questionnaires on layout and navigation of the web application, data input, report (layout and content) as well as background information. This approach resulted in an iterative feedback-driven development of the graphical user interfaces as well as the backend system. The process was quite time consuming but necessary to meet the needs of the DSS users.

Since the simulation is driven by temporal high resolution climate data ranging from 1971 to 2100 and covers entire Germany the amount of data is that large that it is inconvenient to offer a download of the DSS as a desktop application. Furthermore, the software requirements regarding installation and setup of databases, compilers and interpreters are so complex that it would be very challenging for average users to get the system running on their computers. Therefore, it was decided to offer the system as a web-based DSS, where the user requests are processed on a server having all necessary software and data readily available. Since the DSS deals with climate projections ranging over 130 years covering entire Germany and a number of other spatial data sets, the database containing the input data is not small (approx. 28.5 gigabyte storage volume; climate data already comprise more than 98 Mio. records with 22 fields). Additionally, this architecture avoids license conflicts since we were not allowed to share some of the input data unprocessed.

Due to the heterogeneity of the stakeholder group, opinions about purpose of the system and the presentation of the results were quite diverse. Forest practitioners were highly interested in evaluating actual forest stands regarding tree species selection and rotation periods whereas lobbyists were more interested in getting a larger picture of the projected changes on a regional level as well as information about climate change and impacts on forests in general. However, forest practitioners asked as well for an overview of the changing climate and the different risks for forests. They were particularly interested in the location of hot spots and how much they are affected in comparison to others. A summarizing fact sheet containing objectives of the DSS, target audience, application scenarios and derived functional and technical requirements is given in Table II.1. Because of the trade-offs between

flexibility/complexity and processing time, we decided to serve the diverging demands by splitting the system into different components.

The dynamic component allows the user on-demand simulations based on user inputs regarding geographic location, detailed stand characteristics, soil type and topography. Because the number of possible input combinations is infinite, preprocessing the results was not feasible. Simulation results could not be presented in direct response, as we experienced simulation times of several minutes and users of websites usually do not tolerate response times longer than about 30 seconds [Nah, 2004]. Therefore, the user will initiate a simulation online and receive the results in form of a PDF attachment via email when ready. Thus, the web application needs a registration and authentication process with validated email addresses and a job queue.

We tried to achieve a balance between the trade-offs flexibility/complexity on one hand and response time on the other hand, by providing a second component. It offers preprocessed results generated in advance with the dynamic simulation system. The results can be requested from a database through the web application and presented immediately. Thus, only a limited number of input combinations can be offered. In contrast to the dynamic component, the climate input data are not downscaled and results are provided at the original resolution of the climate data (20 km pixel size). To cover entire Germany more than 1200 cells are needed. At 1 km resolution it would be even about 415.000 cells. Furthermore, the user can select from up to ten different soil types and five tree species but the stand characteristics and topography are kept constant. The combination of climate data cells with five tree species and at maximum ten soil types summarizes to 34.870 preprocessed simulation results to be stored. In contrast to the dynamic component the forest stands are static, i.e., they do not grow, to isolate the influence of the changing climate from effects of different stand characteristics. Therefore, the results have to be interpreted as indicators to assess the magnitude and direction of changes on a regional level.

The input data and the simulation results of the preprocessed component of the DSS are also presented in the form of interactive overview maps (WebMap component) within the web application. This proved to be a very accessible way to compare changes in different regions and to provide an impression of the projected change in general [Dransch et al., 2010]. Since the number of results and hence map layers is already large, we provide information only for the most frequent soil type. Less common soil types seemed to add local variation but did not change the overall pattern.

The background information system is the last component of the web application. It contains detailed information about the input data, especially the climate projections, the employed models and their parametrizations and the overall structure of the DSS.

Table II.1.: Fact sheet of DSS scope and requirements defined in the stakeholder process.

1. Objectives

Provide information for developing adaptation strategies for forest management valid for entire Germany

2. Target group

Decision-makers in forestry as well as political actors in the forest sector

3. Use cases

a) Decision-maker in forestry (target group 1) searches for information about tree species selection considering climate change for a specific area/forest stand

b) Political actor (target group 2) looks for Germany-wide information about the changing climate and its impact and potential hazards for forests

c) User of the web application (target group 1 or 2) quarry for background information on climate scenarios and employed models

4. Functional requirements

Regarding use case a)

- easy data input (e.g., default values, drop-down lists)
- defining location via input of coordinates or interactive map
- offer a set of relevant soil types for selected coordinates
- support soil type selection by short descriptions/images
- comparative presentation of different tree species
- presentation of results as table
- presentation of results as charts
- include legends and explanations
- ample links to background information

Regarding use case b)

- interactive map application
- selection of various thematic maps
- base maps for orientation
- map legends
- links to background information

Regarding use case c)

- hierarchical presentation of information about
 - climate scenarios
 - core concept
 - submodels

5. Technical requirements

The use cases described above are best realized by different components within a common web application. The following components can be derived from the three functional requirements:

Evaluation of tree species

- WebMap component
- dynamically filled menus (database connectivity)
- geodatabase with input data and preprocessed scenarios
- master model for database query and submodel linkage
- self-registration and user management module
- job queue for execution of on-demand simulations
- graph library for chart output
- report generation library

Interactive maps

- WebMap component
- map server
- integration of map services

Background information

- content management system or static web pages

The different components have to be integrated into one web application which requires a webserver. For fast development, high code quality and easy maintenance the application should be based on proven software frameworks and libraries instead of individual developments from scratch

Resulting from the stakeholder process the core of the DSS is a simulation system describing the different impacts of climate change on forests. To serve the needs of the stakeholders the simulation system has to deliver information on:

- site index,
- risk of drought induced mortality,
- risk of wind damage,
- risk of pest hazards, and
- economic assessment of changes.

Impacts by fire events, fungi, viruses, and snow-breaks have been considered to be less important for Germany compared to the ones selected by the stakeholders and are, therefore, not included in the DSS. This is in good accordance with the results of a survey of the forest administrations of the federal states of Germany [Bolte et al., 2009b]. The simulation system is the backend of the user-specific on-demand component and also used with reduced complexity for preprocessing the data for the other components, i.e., the overview maps and the preprocessed component. The simulation system consists of input data and various submodels coordinated by a master model. The master model links climate-sensitive submodels simulating forest growth potential, soil water, wind as well as insect phenology and aggregates the projected growth and risks into an economic assessment. These submodels depend on further models delivering the required input data resulting in the following model collection:

- a climate data downscaling component,
- a vegetation period model,
- a rooting depth model,
- a site index model,
- a stand generator,

- a leaf and stem area index model,
- a soil water simulation model with integrated drought stress mortality risk model,
- a three-dimensional wind simulation model with integrated wind damage risk model,
- a pest simulation model for spruce and pine with integrated damage risk model,
- a stand growth simulation model, and
- an economic assessment.

Before we describe the master model, i.e., the schedule of submodel linkage, we present some conceptual fundamentals. To keep input data requirements and simulation complexity manageable, we used a point-based approach, meaning we run the simulation for a point location specified by the user. All input data, i.e., downscaled climate, soil, topography and nitrogen deposition, is mapped to the spatial resolution of the input data with the coarsest resolution, in our case (see below) the downscaled climate data with 1 km grid cells. Additionally, the user can change some of the input values if better information is available. The user can choose from a set of typical soil types at the selected point location and provide relief information. This approach ignores the land cover of the point's neighborhood. This is partly due to the fact that most models do not take the neighborhood into account, like the soil water model, and most users are not able to provide the required information. However, the wind model considers the surrounding relief and the stand growth model simulates a representative forest stand of a quarter hectare centered at the point location including competition on tree level. Thus, the spatial scale of the DSS is determined by the spatial scale of input data and the master model itself is scale-independent.

The models are connected by data exchange in a coordinating time interval of 10 years. The coordinating time interval determines the update frequency of the submodels which is not necessarily identical with their internal time step. For example, the risk models get updated forest stand information every 10 years but the stand growth model runs internally with a 5 year time step and the soil water and wind models run with a daily time step. In some cases data collections are exchanged at the coordinating time interval providing information at a higher temporal resolution, e.g., the vegetation period model offers an array with yearly start and end dates and the soil water model provides an array of soil moisture indices at daily intervals for the wind damage model. Therefore, the coordinating time interval defines the maximum feedback interval.

To keep the complexity and processing time at bay, we refrained from introducing feedbacks between the damage models and the stand growth. The stand growth model describes a growth potential and risks are defined as loss of part of the stand in percent of the area. Thus, damage does not occur at single tree level and does not alter the stand structure. This simplification must be kept in mind when interpreting the simulation results. It also means that the predisposition of forest stands to pest infestation caused by wind throw events is not represented in the simulation. Since pest control management can reduce these risks considerably, this simplification seems justified.

Beside the coordinating time interval of 10 years, there is an output time interval of 30 years. This is according to the usage instructions of the climate scenario data [DKRZ, 2007] ensuring results of the climate model are interpreted as climate trends and not as single events at specific years.

Output variables of the DSS are:

- site index (tree height at age 100),
- risk of wind damage,
- risk of pest hazards,
- risk of drought induced mortality,
- wood production value, and
- risk costs.

For the output time interval the results of the coordinating time interval are averaged for the site index using an arithmetic mean. For the risks the aggregation is calculated as follows:

$$Risk_{30} = 1 - (1 - Risk_{1-10}) \times (1 - Risk_{11-20}) \times (1 - Risk_{21-30}) \quad (II.1)$$

where $(1 - Risk)$ gives the conditional survival probability of the respective coordinating time interval [for details, see Staupendahl, 2011]. The 10-year risk values are aggregated for all risk types to 30-year drop out probabilities. Afterwards, the 30-year risks of all risk types are aggregated to a total risk value in the same manner:

$$Risk_{total} = 1 - (1 - Risk_{biotic}) \times (1 - Risk_{drought}) \times (1 - Risk_{wind}) \quad (II.2)$$

The total conditional probability that a stand, that survived until the beginning of a 30-year period still exists at its end, is one minus the total risk. The economic assessment is based on the aggregated site indices and the total drop-out probabilities ($Risk_{30}$) and delivers wood production value and risk costs of 30-year periods.

The driving forces of the simulation are the daily climate data available for the time periods 1971-2000 and 2010-2100. In the second period the simulation is carried out once for each of the climate scenarios (A1B and B1). The topography and the soil characteristics are assumed to be constant over the considered periods, whereas the climate and the nitrogen deposition are available as time series derived from scenarios of possible future development.

The master model is characterized by two nested loops representing the 30-year output and the 10-year coordinating time period, as described above. Figure II.3 contains a schema of the master model including input data, submodels and process flow. A simulation run is started based on the user provided information (starting time, point location, soil type, tree species and optional elevation) together with the corresponding soil parameters and the topography of the neighborhood. The simulation always runs till the year 2100, so the number of iterations depends on the user selected starting time. To provide a reference for the climate projections the DSS offers, additionally to the starting times 2011, 2041 and 2071, the starting time 1971. Since there is a 10-year gap between the reference period and the future periods the stand growth model continues in this case for ten years outside of the loops.

The 10-year coordinating time interval starts with loading and preprocessing daily climate data and yearly nitrogen deposition in yearly resolution for the current time interval.

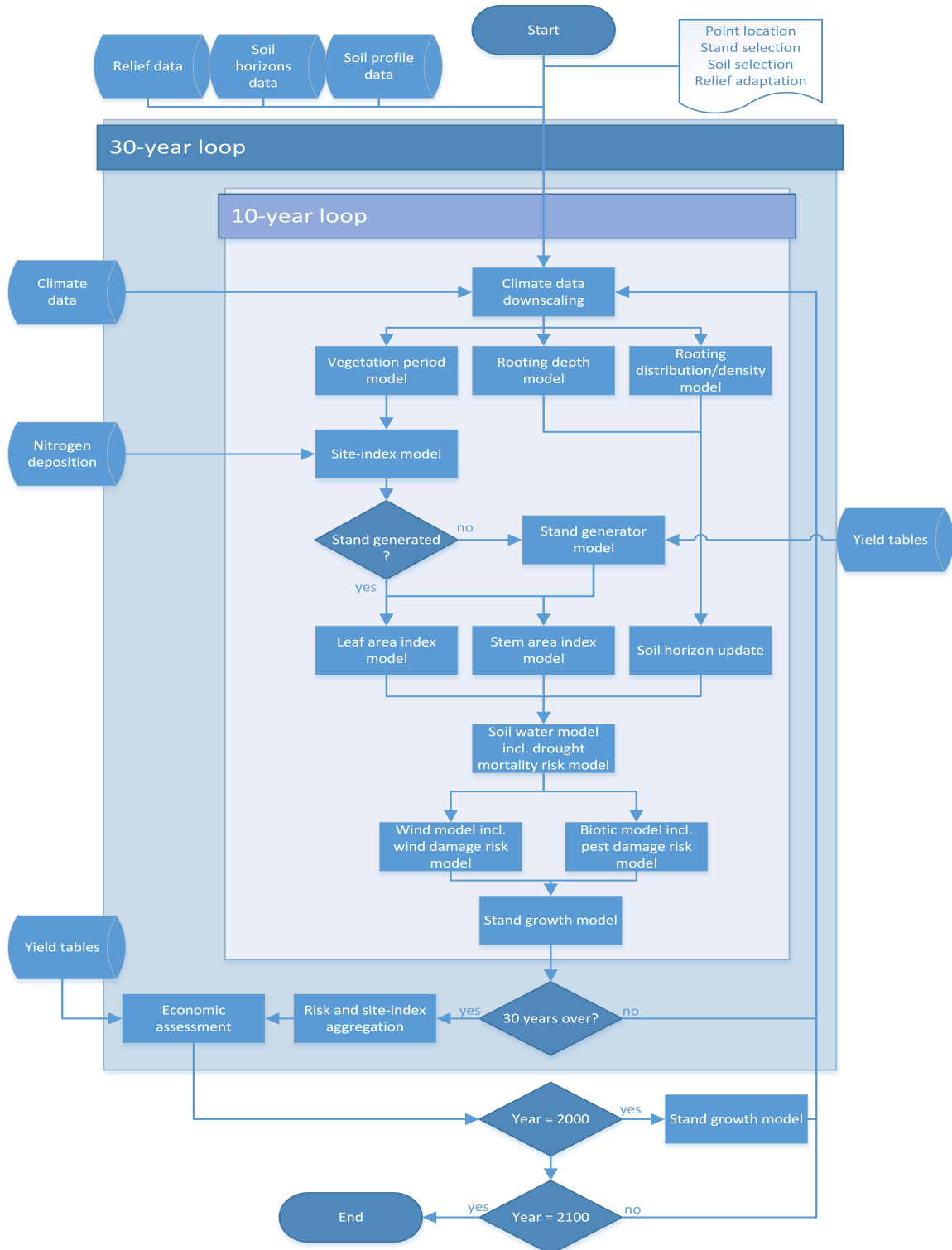


Figure II.3.: Schema of the master model including input data, submodels and process flow.

Climate data of the 3 x 3 neighborhood of the user selected location provide the spatial support in the downscaling module following the recommendations of the usage guidelines of climate projections [DKRZ, 2007]. The downscaled climate data are then used to calculate the start and the end of the vegetation period for every year within the coordinating time interval. The vegetation period model also provides climatic water balance, mean yearly temperature, annual precipitation as well as mean temperature sum within the vegetation period. The rooting depth, soil horizon update routine and root density/distribution model based on the forest stand and soil characteristics run parallel. On the basis of the results of the vegetation period model, the soil characteristics and the nitrogen depositions the site-index model estimates the growth capacity. The site index is the main input for the forest stand growth and stand generator. In the first iteration a forest stand is created by the stand generator using yield tables. This virtual forest stand is then grown throughout the rest of the simulation. The generated stand provides the necessary information for the leaf and stem area index. Having stand, soil and climate data available, the soil water model including a drought stress mortality risk module can be run. It returns the mortality risk as well as soil water indices. The soil water information is an important input for the wind and the biotic risk models. The wind model needs additional information about location, topography, stand characteristics including rooting depths, and daily climate. The model describing the biotic damage to spruce pine requires location, stand age, soil water as well as climate data. Updating the site index and growing the virtual forest stand in preparation for the next iteration is the last step in the 10-year loop.

After three iterations of the inner 10-year loop, risk and site indices are aggregated and the economic assessment carried out. If the end of the simulation period is not yet reached the 10-year loop is entered again.

Please refer to the listing of the in- and output variables of the submodels in Digital Supplement 1 to gain a deeper understanding of the interdependencies of the submodels.

II.2.4. Implementation

Building on the requirements resulting from the stakeholder process and the concept of the simulation present as a composition of input data and submodels in the master model we now outline the implementation of the reference system.

Data and Database

Since the DSS shall provide valid results for entire Germany, datasets covering the whole country were needed for the reference implementation. This proved to be a severe restriction resulting in coarser resolution of some input data because data of high spatial resolution is only available for parts of Germany. However, as the master model itself is scale independent, it is possible to exploit high resolution data when applied locally as shown in Thiele et al. [2010].

For the reference implementation following input data sources were used:

1. **Relief** information is derived from digital elevation models based on the Shuttle Radar Topography Mission (SRTM) dataset Version 4 edited by the CIGAR Consortium for Spatial Information in 3' resolution, i.e., approx. 90 meters [Jarvis et al., 2008] and aggregated to the required target resolution of 1 and 20 km, respectively.

2. **Soil** data consisted of 124 soil types as defined by the Forest Soil Map [Wald-BÜK 1:1 Mio., Richter et al., 2007]. The user can select from maximum 10 typical soil types at each location. The soil types provide information about available soil water capacity, effective cation exchange capacity, and groundwater depth. More detailed information such as bulk density, stone content, organic matter, available field capacity is provided for the separate horizons.
3. Annual deposition rates of **nitrogen** are preprocessed with the MAKEDEP model [Alveteg et al., 1998] and stored at a spatial resolution of 1 km.
4. **Forest stand** information is generated based on a combination of user input, climate sensitive site index model, yield tables [Schober, 1995; with adaptations by Wollborn and Böckmann, 1998], and the stand generator included in TreeGrOSS [Döbbeler et al., 2002, Nagel, 2011]. For the economic model additional yield tables generated with TreeGrOSS are preprocessed and stored in the database.
5. As **climate** forcing data the climate scenario 20C3M for the period of 1971-2000 (reference) and SRES A1B and B1 [IPCC, 2000] for the period of 2011-2100 modeled by coupled AOGCM ECHAM-5-MPIOM (run 1). The data were regionalized with the Climate-Local-Model (CLM) [Hollweg et al., 2008] and interpolated to the spatial resolution of 0.2° [Datastream 3; Lautenschlager et al., 2009a,b] in daily time step. The climatic data were then bias corrected using the observation data of the German Weather Service, implementing the delta-change and linear transfer functions [Mudelsee et al., 2010]. The vapor pressure was adjusted to bias-corrected temperature.

The selection of a relational database management system (RDBMS) with spatial extension was based on a simplified utility-analysis (see Table II.2) at the time of implementation (2008). The most common RDBMS offering support for spatial data were compared regarding different criteria. The solution with the highest utility value was selected. To facilitate reusability and code transparency we focused on free and open source software (FOSS) with one exception due the very limited offer of FOSS licensed solutions at that point.

Based on the utility-analysis we selected the RDBMS PostgreSQL [The PostgreSQL Global Development Group, 2015] with the spatial extension PostGIS [Refractions Research, 2015]. PostgreSQL is a free and open-source object-relation database management system. PostGIS follows the Simple Features for SQL specification from the Open Geospatial Consortium [OGC, 2010] and adds geographic objects and functions to PostgreSQL.

Table II.2.: Utility-analysis of most common Geodatabase solutions (utility values per category from 0 to 4, where 4 is the best value; equally weighted).

	Oracle Spatial	MySQL + Spatial-Extension	PostgreSQL + PostGIS-Extension
Version	11g	5.0.51	8.3.1
License	proprietary	GPL	PostgreSQL + GPL
ACID conformity	4	2	4
Referential integrity	4	4	4
max. DB size	no/4	no/4	no/4
Save geometries	3	2	4
Geodata processing	3	1	4
OGC SFS	4	1	4
Utility value sum	22	14	24

Since this DSS is concerned with the impact of climate change on forest stands climate data are important in the data model. The table containing the spatial location of the CLM cells and the relief information needed for downscaling is central in the data model (see Figure II.4 for visualization on table level; see Digital Supplement 2, for model visualization on field level). The tables with the climate projections as well as the tables concerning the job queue link to it. If a user asks for a simulation run of the dynamic component, the request is stored in a table which is checked every 15 minutes by a cron job that also starts the next simulation. A list of finished and failed jobs is kept for later inspection. The nitrogen deposition is stored at the resolution of the SRTM elevation model. Hence, both tables are connected via a table containing the spatial location of the SRTM cell centers. The ten most common soil types at each CLM cell are stored to be presented to the user in a selection list. The soil types are connected to the horizons that constitute the respective profiles. All yield tables of the considered tree species are stored in one table and accompanied by a table of initial stand characteristics. Another set of tables caters the preprocessed component of the DSS (see Figure II.5 for visualization on table level; see Digital Supplement 2, for model visualization on field level). They contain information about the spatial extent of the preprocessed simulation runs, the considered soil types and their properties and finally the simulation results.

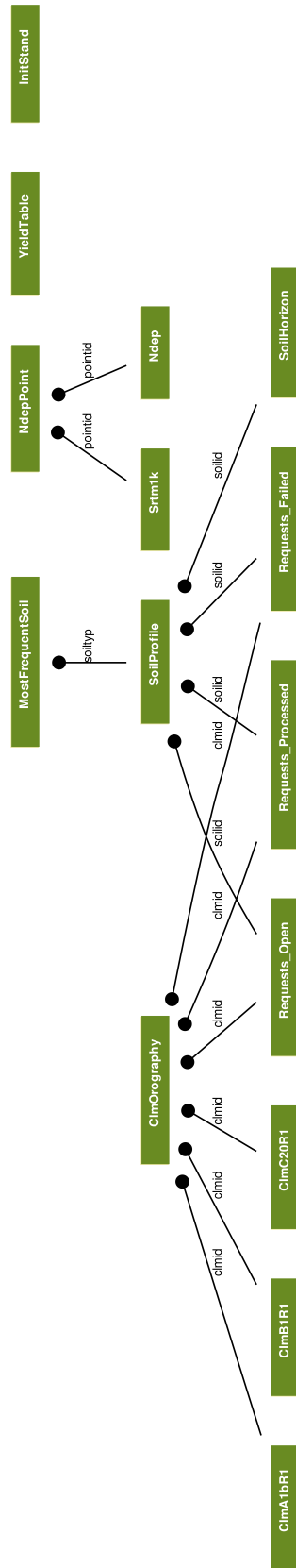


Figure II.4.: Data model of input data on table level for the dynamic simulation component. The connecting lines visualize relations between fields of different tables (see Digital Supplement 2, for model visualization on field level).

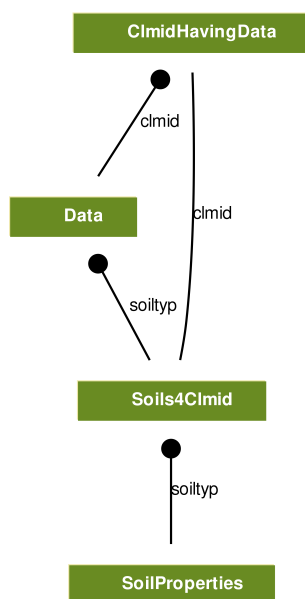


Figure II.5.: Data model of the preprocessed component on table level. The connecting lines visualize relations between fields of different tables (see Digital Supplement 2, for model visualization on field level).

Software

The implementation of the web-based DSS relies on a web framework for common activities such as database access, session management, input validation, templating. Using standard components especially for security aspects keeps the source code compact and frees resources for the development of the DSS. To select the most suitable framework we assessed three widely used web application frameworks all associated with different programming languages using a simplified utility-analysis (see Table II.3). We selected Django [Django Software Foundation, 2015], a web-application framework for the programming language Python [Python Software Foundation, 2015]. More precisely we used Django together with additional spatial functions for building GIS Web applications distributed as GeoDjango [Foundation, 2015]. Selecting this framework we also choose Python, a general-purpose, high-level programming language designed for high readability, fast development and small codes. Django follows the model-view-controller architectural pattern and is, therefore, especially suitable for database-driven applications coming with an object-relational mapper. Many common features needed for web-applications are already on-board or are available through extensions. In particular we used the user authentication, which is shipped with Django and added the registration extension [Cutler, 2015]. Users have to register themselves and provide a valid email address because the dynamic component sends simulation results as PDF via email. To generate the PDF files containing text, tables and figures we employed ReportLab [ReportLab Inc., 2015] a free and open-source engine for creating data-driven PDF documents written in Python. To dynamically generate the HTML pages

we used the Django templating language and the Cascading Style Sheets (CSS) framework YAML [Yet Another Multicolumn Layout, Jesse, 2013] for layout and styling.

Table II.3.: Utility-analysis of different web-application frameworks (utility values per category from 0 to 4, where 4 is the best value; equally weighted).

	(Geo-) Django	Ruby on Rails	Struts 2
Version	0.96	2.0.2	2.0.11
License	BSD	MIT	ASL
Language	Python	Ruby	Java
Object-relational mapper	4	4	4
Security framework	4	3	3
Template system	4	4	4
Form validation	4	4	4
Session management	4	4	4
Caching system	4	4	3
Model-View-Controller paradigm	4	4	4
Native GIS support	4	1	1
Performance	4	3	2
Development speed	4	3	2
Utility value sum	40	34	31

WebMaps were needed at two different places in the web application: 1) location selection via a mouse-click within a zoomable map, 2) presentation of the main parameters and preprocessed results as interactive maps. Non trivial WebMap applications consist usually of two parts, a client-side application presenting the maps in the browser and a map server providing map layers in form of images. We selected the client-side OpenLayers JavaScript library [OpenLayers Contributors, 2015] after an evaluation of common libraries (see Table II.4). For the WebMap in the preprocessed component we implemented the user interface (UI) using GeoExt [GeoExt Community, 2010]. GeoExt is a JavaScript library connecting OpenLayers with additional UI-functionalities of ExtJS [Sencha Inc., 2015a,b], for building complex WebMap application on the web. It offers a clearly arranged and very accessible layer tree providing structure for the numerous map layers.

Table II.4.: Utility-analysis of different web mapper frameworks (utility values per category from 0 to 4, where 4 is the best value; equally weighted).

	OpenLayers	WMS Mapper	Mapbender	Mapbuilder
Version	2.5	0.03	2.4.5	1.0.1
License	BSD	AFL	GPL	LGPL
Zoom bar	4	0	0	0
Panning	4	0	4	2
Tiling	4	4	0	0
Layer overview	3	0	4	4
Proprietary layer	3	0	0	0
Client side	4	4	0	0
Extensible	4	2	3	2
Memory usage	4	4	1	1
Utility value sum	30	14	12	9

For providing the maps of input and preprocessed data to OpenLayers we also needed a map server creating and delivering the requested maps through the Web Mapping Service (WMS) standard [OGC, 2015]. We selected the UMN MapServer (see Table II.5) and defined the required mapfiles containing the definition of the data source and styling of the various map layers.

Table II.5.: Utility-analysis of different map server (utility values per category from 0 to 4, where 4 is the best value; equally weighted).

	UMN MapServer	GeoServer	degree
Version	5.0.2	1.6	2.1
License	MIT	GPL	LGPL
Performance	4	2	2
Legend	4	4	4
WMS standard	4	4	4
Server demands	4	1	1
Utility value sum	16	11	11

Beside the presentation of selected maps the full range of preprocessed results can be requested via the web application and are presented directly in the browser. The results are loaded for a user selected location, soil type, and tree species. The user can switch between a table and chart view. The tables are constructed via the Django templating language and the charts are requested from the Google Charts API via the GChart Python Wrapper for Django [Quick, 2009].

A major part of the DSS is the dynamic component driven by the master model. Although the master model itself is not a web application it nevertheless uses the web framework because the connection to the database is conveniently encapsulated with the object-relational mapper and comes with needed spatial functions. The master model is responsible for the

flow of control and data as well as managing the state of the models. The last point is essential because some of the submodels must keep their state from one iteration to the next. The soil water model, for example, must keep the state of soil water between two 10-year periods and continues with an updated forest stand and new climate data in the next iteration. Furthermore, the output of one submodel serves as input of other submodels resulting in an intensive exchange of a large amount of data. Since exchanging data via input and output files is very slow and error-prone, especially when multiple simulations run in parallel on one computer, we decided to make all models directly accessible at run-time. Submodels implemented by us were written in Python facilitating easy data exchange and flow control. However, several submodels have been delivered in programming languages other than Python (cf. Table II.6). Therefore, we needed to implement wrappers for the submodels to facilitate interchangeable data types and flow control across submodels, e.g., instantiation and function/method calling from Python.

Two submodels had to be rewritten since the provided code base could not be incorporated into the master model. The soil water model was originally implemented in Visual Basic, a language native to Microsoft Windows. The model makes extensive use of Windows specific libraries and thus cannot be executed under Linux by the development and runtime environment Mono [Mono Project, 2015]. Furthermore, the implementation does not adhere to the object-oriented paradigm making it difficult to store and clone complex soil water states. Since the soil water model runs internally with a daily time step, it is performance critical for the entire master model. Therefore, we decided to re-implement the model in C++ [Standard C++ Foundation, 2015] following the object-oriented paradigm.

The second submodel rewritten was the economic assessment, as it was delivered in form of an Excel spreadsheet. Since the model is only executed in the outer 30-year loop, performance is not crucial and we re-implemented the Excel calculations in Python easing data exchange and control flow. A transformation of the Excel spreadsheet into an OpenOffice spreadsheet which could be connected to Python through the pyUNO bridge [Apache OpenOffice, 2010] would have been an alternative but would have come with enormous dependencies.

Table II.6.: Listing of submodels with programming languages other than Python and employed wrapper libraries.

Submodel	Programming Language	Wrapper library
Climate data downscaling	Fortran	F2PY [The Scipy Community, 2014]
Site-index model	R	RPy2 [Gautier, 2014]
Soil water model	C++	SWIG [SWIG, 2015]
Wind model	Fortran	F2PY [The Scipy Community, 2014]
Biotic model	R	RPy2 [Gautier, 2014]
Stand growth model	Java	JCC [Apache Software Foundation, 2012]

All submodels are split into separate modules making it easy to replace submodel implementations. This is especially true for submodels implemented in Python. Submodels

written in other programming languages come with an overhead. The necessary wrappers are described in the following.

The climate data downscaling model and the wind model are implemented in Fortran. We used the command line tool F2PY [The Scipy Community, 2014] to compile the Fortran source code into a dynamic library containing Python wrappers (cf. Figure II.6). The dynamic library is then loaded from Python and Fortran functions are called directly. The different data types are also converted from Fortran to Python and vice versa by the wrapper code in the dynamic library.

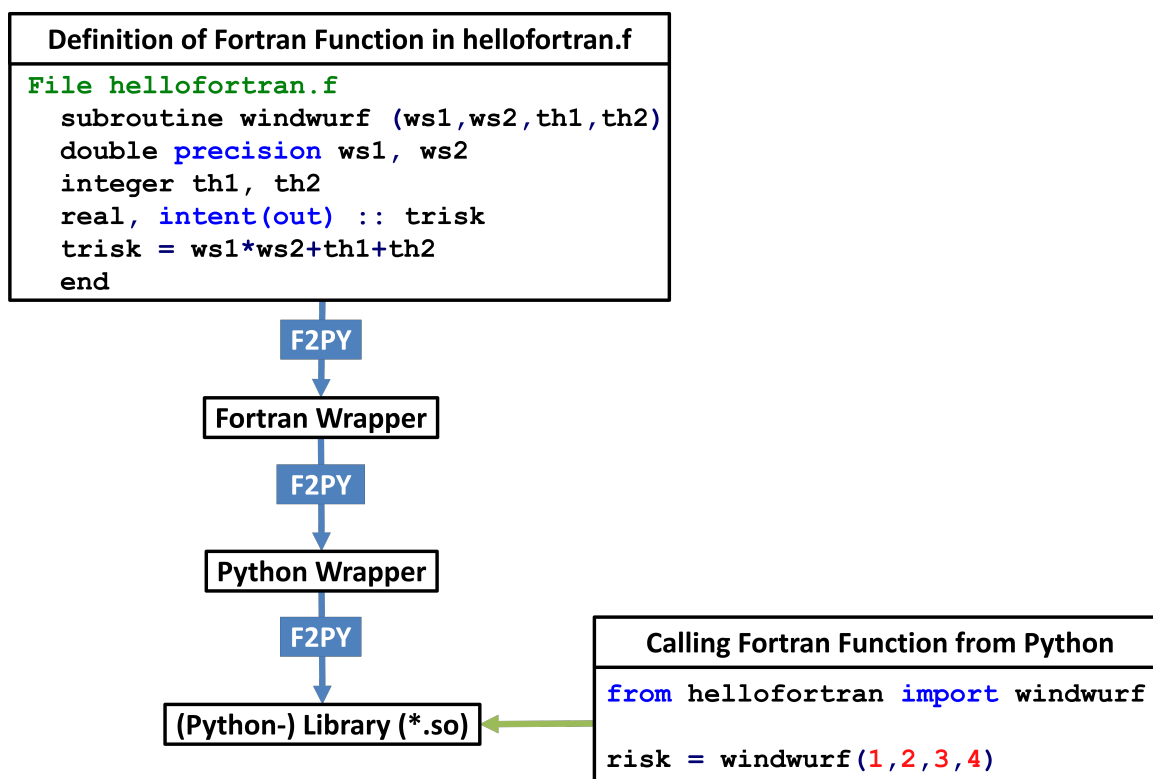


Figure II.6.: Simplified example of wrapping Fortran code to gain access from Python using F2PY. Green arrow indicates access from Python at run-time. Blue arrows indicate transformations from original Fortran code into a Python library generated by F2PY in advance.

Integration of models provided as R scripts and R objects (site-index model and the bi-otic risk models) was achieved with the RPy2 package [Gautier, 2014]. RPy2 provides an interface to R from Python. It is not necessary to create individual wrappers since the RPy2 package allows to call R functions from Python and transforms data structures between the two languages (cf. Figure II.7).

We used JCC to make the stand growth model written in Java callable from Python. JCC is a C++ code generator for calling Java from C++/Python [Apache Software Foundation, 2012]. JCC first generates a C++ wrapper for public Java methods and then a Python wrapper on top. Before JCC can do its work the Java source code has to be compiled with a Java compiler to a Java class file or a Java Archive (JAR). All of this is finally bundled into

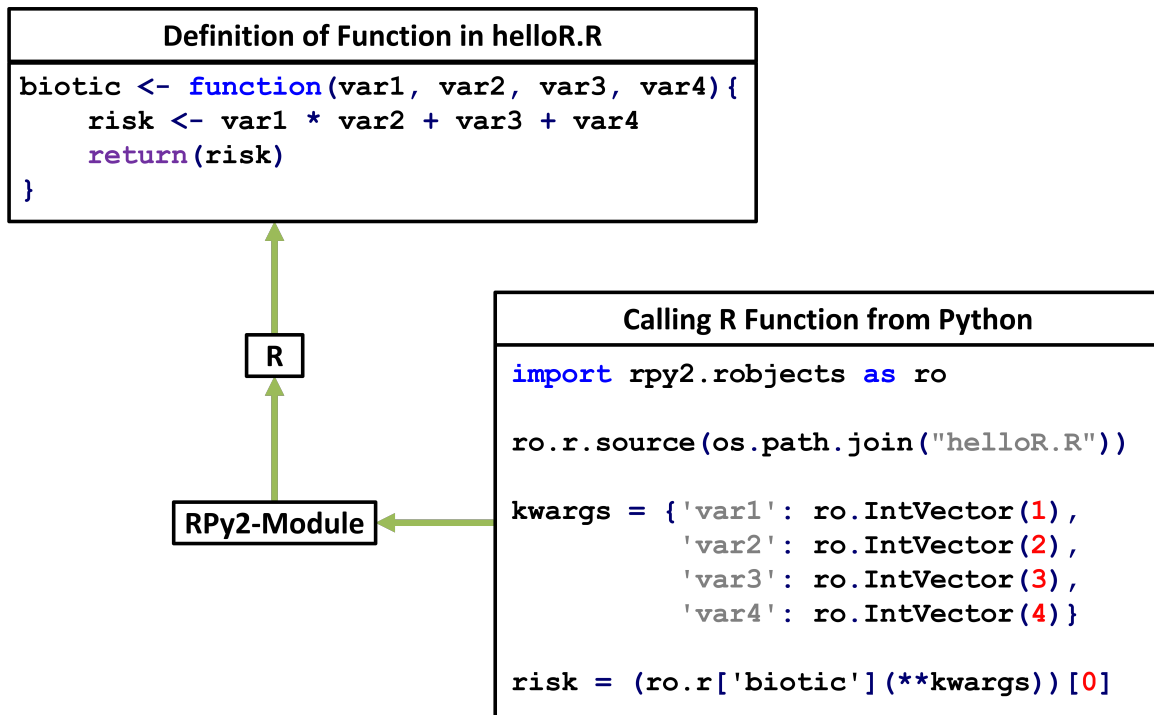


Figure II.7.: Simplified example showing how to call an R function from Python using RPy2. Green arrows indicate access at run-time.

a Python-Egg (cf. Figure II.8). JCC requires a Java Runtime Environment to operate and provides functions to start a Java Virtual Machine from Python.

The soil water model, for performance reasons written in C++ (see above), was made available to Python using the Simplified Wrapper and Interface Generator [SWIG, 2015], a tool to connect C and C++ code with several high-level programming languages. Data types, imports, functions and variables were declared in an interface file, which is then compiled using SWIG, resulting in a C++ wrapper and a Python module. In a second step the original C++ source code is compiled together with the wrapper using a C++ compiler such as GCC [Free Software Foundation Inc., 2015] and the resulting object files are packaged into a shared library. The Python module provides access to the shared library. The workflow is similar to the F2PY tool but needs more manual steps (cf. Figure II.9).

Having discussed all submodels and wrappers we now turn to the parts of the master model implemented as class ModelEngine. The constructor of the class ModelEngine takes the user input (as described above) as arguments. Compulsory arguments are longitude and latitude, the soil type, the tree species, age and yield class as well as the start year. Optionally the user may provide more precise information regarding elevation, aspect and slope at the specified location. Furthermore, an indicator argument handles soil water model errors and reduces the step size of the integration interval if necessary. Moreover, static input data such as relief and soil data are loaded from the database and all information is stored as class members. Finally the constructor initializes or instantiates the submodels and stores the objects as class members as well.

The starting point for the simulation is the method taking care of the outer 30-year loop. It takes two arguments defining start and end of the simulation time span. After initializing an

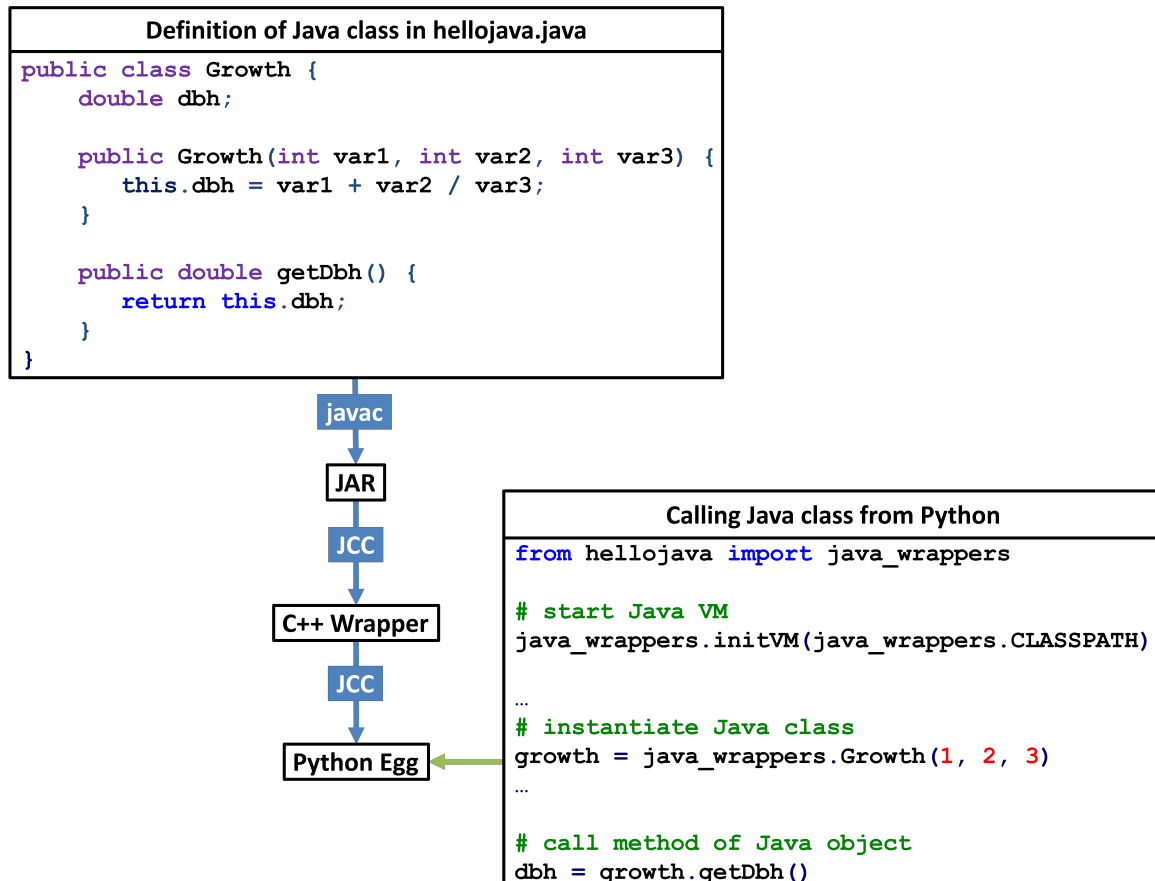


Figure II.8.: Simplified example showing how a Java class can be called from Python using JCC. The green arrow indicates access from Python at run-time. Blue arrows indicate transformations from Java code to a Python-Egg (i.e., a single-file importable Python project) generated in advance.

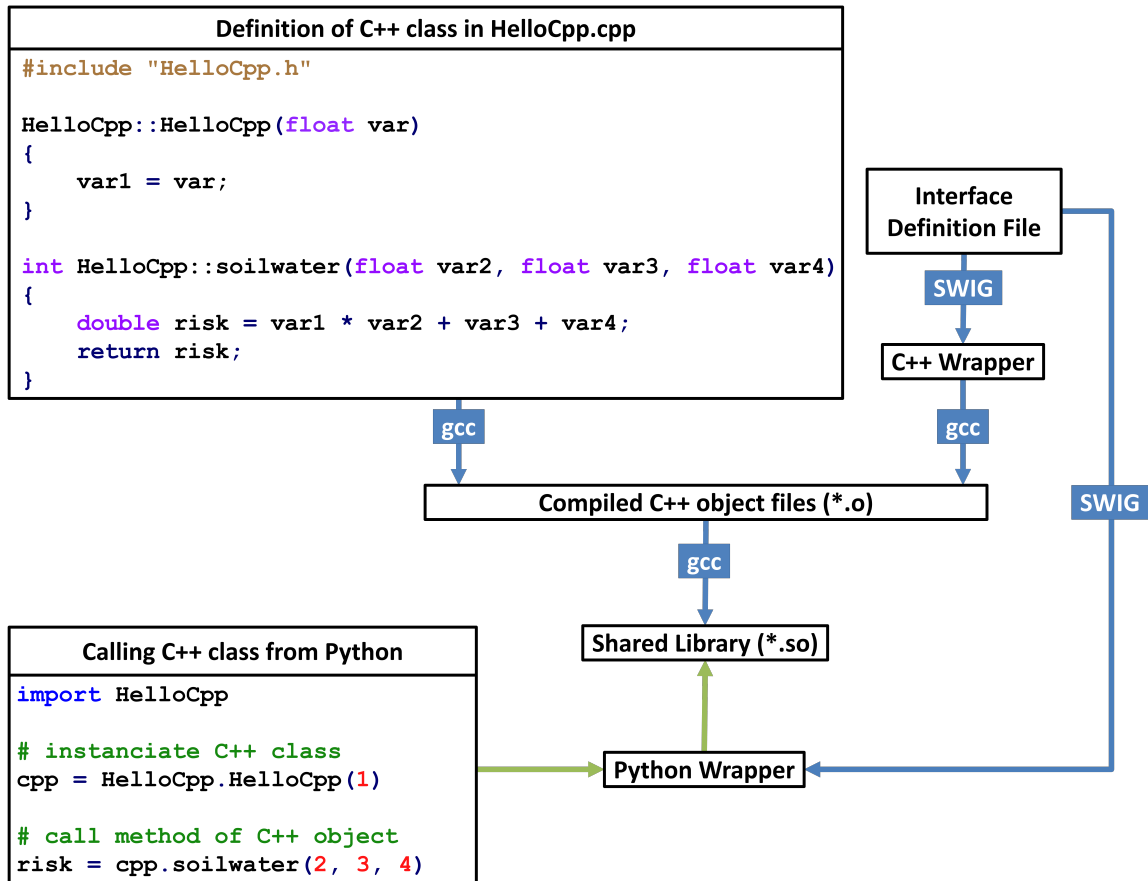


Figure II.9.: Simplified example of wrapping C++ code to gain access from Python using SWIG. Green arrows indicate access from Python at run-time. Blue arrows indicate transformations from C++ code into a Python library.

empty dictionary to store the results of the 30-year output intervals the inner 10-year loop is run three times. The method coordinating the 10-year loop calls sequentially the methods dealing with the different submodels and some helper methods, e.g., for data handling (see Table II.7). The output of the three 10-year time intervals is aggregated and stored in the results dictionary. The economic assessment submodel runs on the aggregated values.

Table II.7.: List of method and function calls in inner 10-year loop in the order of execution.

No.	Function/Method	Module	Description
1	calculate_days_and_dates	mastermodel	Calculate start and end dates
2	get_clm_climate_data	input	Load and prepare climate data from database
3	regionalize	submodels.downscaling.downscaling	Run downscaling submodel (Interface to Fortran)
4	moistureCorrection	submodels.downscaling.downscaling	Run bias correction of moisture/humidity in CLM data (Interface to Fortran)
5	calc_veg_period	submodels.phenoalometric.vegperiod	Call the vegetation period submodel
6	calc_nutrient_number	submodels.soilparameters.nutrients	Calculate a soil nutrient class for site-index
7	calculate_rootdepth	submodels.phenoalometric.rootdepth	Calculate rooting depth
8	update_soilhorizons	submodels.soilparameters.changesoil	Update soil profile considering rooting depth
9	set_soil_to_brook	submodels.soilwater.handler	Set soil characteristics within soil water submodel (Interface to C++)
10	change_DRAIN	submodels.soilwater.handler	Change DRAIN parameter of soil water submodel (Interface to C++)
11	calc_rootdensity	submodels.phenoalometric.rootdensity	Call the root density calculation
12	get_nitrogen_deposition	input	Load and prepare the nitrogen deposition data from database
13	get_site_index	submodels.siteindex.handler	Call the site-index submodel (Interface to R)
14	get_yieldtable_values_from_yieldclass	input	If stand was not created so far, load and prepare initial stand characteristics from database
15	generate_stand	submodels.standgrowth.handler	If stand was not created so far, call the stand generator submodel (Interface to Java)

16	calc_maxlai	submodels.phenoallometric.lai	Call the leaf area index submodel
17	calc_sai	submodels.phenoallometric.lai	Call the stem area index submodel (Interface to C++)
18	set_standparameters_to_brook	submodels.soilwater.handler	Send stand characteristic to soil water submodel (Interface to C++)
19	reduce_climatic_arrays	mastermodel	Reduce time series of climate data to 10 years
20	set_climate_to_brook	submodels.soilwater.handler	Send climate data to soil water submodel (Interface to C++)
21	run_brook	submodels.soilwater.handler	Run the soil water submodel (Interface to C++)
22	run_scadis	submodels.wind.handler	Run the wind risk submodel (Interface to Fortran)
23	run_ips_typo_model	submodels.biotic.handler	If tree species spruce is simulated, call the <i>Ips typographus</i> risk submodel (Interface to R)
24	run_phy_cyanea_model	submodels.biotic.handler	If tree species pine is simulated, call the <i>Phaenops cyanea</i> risk submodel (Interface to R)
25	run_standgrowth	submodels.standgrowth.handler	Call the stand growth submodel (Interface to Java)
26	update_stand_information	mastermodel	Update the stand characteristics for the next iteration

In case the simulation started with the year 1971 the gap between the reference period and the climate projections is closed by running the stand growth model for 10 years with constant site-index. If the simulation enters the climate projections (start year 2011) the zsimulation is carried out for two climate scenarios (A1B and B1) successively as described above.

In previous sections we gave a comprehensive overview of the architecture of the master model and our reference implementation, but the most truthful and detailed description is the source code itself. It might as well serve as starting point for similar projects in the future. Thus, the source code of the application including the Django-based web application is available at <https://sourceforge.net/projects/dss-wuk>.

II.2.5. Discussion and Outlook

The construction of the DSS 'forest and climate change' started with dummies and prototypes and a stakeholder process, leading to a conceptional model and ended with a successful implementation of a reference system. The stakeholder process provided the information needs of forest practitioners regarding the impact of climate change on forest. The process resulted in a requirements specification for the DSS. Involving stakeholders in the DSS development is very important but nevertheless often neglected leading to systems not accepted by the target audience [Lynch et al., 2000, Lynch and Gregor, 2004]. We, thus, designed the conceptional model and the technical concept on the basis of the collected stakeholder input considering necessary model complexity and simulation time. By carefully heeding stakeholder feedback the DSS received some attention by the target audience [e.g., Haufe, 2011] and was promoted by stakeholders [e.g., Hillmann and Zimmeck, 2011a,b,c]. Nevertheless, the usefulness of the system was impaired by inconsistencies in the climate projections (e.g., average temperature below minimum temperature in some cases) which are communicated on the web page of the reference implementation. We tried to correct for some known biases [see e.g., Lindau and Simmer, 2012], but we have not been able to remedy deficiencies completely. Moreover, the regionalized climate data might not have been adequate for usage at this level. Furthermore, the knowledge needed to parameterize the employed risk models might still be weak. Nevertheless, research on effects of climate change on forests is still ongoing and the creation of such a coupled modeling system helped to point out where further research is needed.

From a technical point of view, we have shown that an integrated system can be built from established models. By splitting the system into different components (dynamic, pre-processed and background information) with different targets concerning reaction time and spatial resolution the application can cater different needs. The whole application is built on well-known frameworks to keep the source base small and therefore easy to maintain. Since the application is highly modularized, submodules can be replaced quickly by other implementations. This is a very important architectural feature as knowledge in climate change impact still increases rapidly and the development of more adequate simulation models proceeds apace. We presented a way to interface established models implemented in different programming languages to use them as building blocks of an integrated DSS. The need of such interfacing mechanisms will increase as climate change impact assessments need to incorporate different impact models into one integrated simulation system.

We inserted our simulation system into a web-application for easy use by forest practitioners. However, the employed framework and our master model can also be run from

the command line or called from other code enabling simulation studies or integration into other systems. We simulated, for instance, the impact of climate change on spruce stands of an entire forest company [Thiele et al., 2010]. Since the Desktop GIS QGIS comes with a Python API, it would be possible to integrate this DSS as a plugin.

The concept as well as most parts of the implementation are generic enough to be adaptable to other regions and spatial and temporal scales. Therefore, we offer our work to anybody interested to learn or build upon it.

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SECTION II.3

Climate Change Impact Assessment - A Simulation Experiment with Norway Spruce for a Forest District in Central Europe

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Authorship

- Robert S. Nuske supported the design and implementation of the data model, the model coupling in R and the writing by language edits of the manuscript.
- Bernd Ahrends supported the implementation of the phenological and allometric models, the nutrient index model, the soil water and drought stress models, the result analysis and the writing by text edits regarding these models.
- Oleg Panferov supported the implementation of the climate downscaling and wind risk model as well as the result analysis and the writing by text edits regarding these models.
- Matthias Albert supported the implementation of the site-index and forest growth models as well as the result analysis and the writing by text edits regarding these models.
- Kai Stuapendahl supported the implementation of the economic model as well as the result analysis and the writing by text edits regarding this model.
- Udo Junghans supported the implementation of the bark beetle model.
- Martin Jansen supported the writing by giving advices on the discussion.
- Joachim Saborowski supervised the writing of the manuscript.

II.3.1. Abstract

Projected climate change implies that site conditions can no longer be expected to remain constant over a tree's lifetime. The fast and complex changes in site characteristics and growth patterns diminish the value of traditional knowledge and profoundly alter the conditions of forest management. One way to tackle the inherent uncertainties are simulation studies addressing these new dynamics and mechanisms. The aim of this study is to present such a simulation model system comprising various established and validated process-based and statistical models assessing the complex and dynamic response of a forest stand to climate change.

For a given climate scenario, these coupled models estimate the potential growth and yield and various risks considering changing site and stand conditions. As an example, the model system is applied to managed forest stands of Norway spruce (*Picea abies* (L.) H. Karst.) in a forest district located in central-western Germany. For the changing climate conditions according to SRES B1 and A1B, the model results suggest a positive effect on the site index and, by contrast, a negative impact on tree survival of increasing risks regarding drought stress mortality, wind damage, and bark beetle infestation given the climate change scenario. The annual contribution margin of timber production under consideration of damage risks by drought stress mortality, wind, and bark beetle infestation reveals that, in this case, the increased growth is able to compensate for the higher risks with few exceptions. Furthermore, we discuss the advantages and challenges of employing a dynamic complex simulation model system for climate change impact assessment based on high-resolution climate data.

II.3.2. Introduction

Changes in global climate are a natural part of Earth's history, but the current rate of change driven by anthropogenic factors is unprecedented [Jansen et al., 2007, Smith et al., 2015]. Global circulation models (GCMs) project increases of global mean annual surface temperatures depending on the emission scenario of between 0.3 and 4.8°C as well as changes in precipitation patterns by the year 2100 [Collins et al., 2013]. Regional climate models (RCMs) account for regional variations by downscaling GCMs to higher spatial resolution, typically between 10 and 50 km [Kotlarski et al., 2014]. Central Europe will likely experience an increase in the annual average air temperature above the global mean as well as a reduction of summer precipitation with a concurrent increase in winter and spring precipitation [Christensen et al., 2007]. Furthermore, increases in the frequency and intensity of extreme weather events such as heat waves, torrential rain, summer droughts, storms, and spring temperature backlashes are projected for Europe [e.g., Ballester et al., 2010, Beniston et al., 2007, Christensen et al., 2007, Raisanen et al., 2004]. A changing climate with an increase in extremes has already been observed in recent decades [e.g., Munich Re, 2011, Trenberth et al., 2007].

Some positive but mostly negative effects of climate change are anticipated for Central European forests [e.g., Lindner et al., 2010, Spathelf et al., 2014]. The projected climatic changes may have positive effects on tree growth, as described, for example, by Albert and Schmidt [2012, 2010], Boisvenue and Running [2006], Hasenauer et al. [1999], Nothdurft et al. [2012], Pretzsch et al. [2014]. However, several biotic and abiotic disturbances (direct as well as indirect) are expected to increase in frequency and intensity. Allen et al. [2010]

as well as Birdsey and Pan [2011], for example, observed an increase in tree mortality as a consequence of drought and heat in forests. Seidl et al. [2008] and Hlásny and Turčáni [2009] have shown an increase in insect infestations. Fink et al. [2009] and Schelhaas et al. [2003] projected an increased vulnerability to wind damage [cf. review by Gardiner et al., 2010]. Furthermore, for some regions, an increased risk of forest fires is expected [e.g., Schumacher and Bugmann, 2006], as well as changes in the frequency and/or intensity of other disturbances such as fungal diseases [e.g., Porta et al., 2008]. However, the reactions of forest ecosystems to changing climate conditions are not uniform but may differ considerably based on stand structure and tree species [Kint et al., 2012]. According to current knowledge, climate change is expected to alter forest production conditions profoundly.

Norway spruce (*Picea abies* (L.) H. Karst.) in Central Europe is expected to be particularly vulnerable to the projected climate change [Hanewinkel et al., 2013]. Because of its high growth potential, timber quality and usability as well as rather modest demands regarding site quality, Norway spruce has become one of the major commercial tree species in Central Europe [Hanewinkel et al., 2013, Yousefpour et al., 2010]. Many stands were planted beyond the natural range of Norway spruce and with high structural uniformity and will probably suffer from low adaptation potential and resilience Brosinger and Östreicher [2009], Spiecker [2000]. An assessment of the anticipated damage risks by disturbance agents to Norway spruce outside its natural range would provide highly needed information for adaptation strategies in Central Europe.

Past forest management planning was typically based on the implicit assumption of constant production conditions over a tree's lifetime. Because of the projected rapid change in the climate, this assumption may become untenable in the future [Lindner, 2000]. In contrast to annual cropping systems in agriculture, where systems can be adapted sufficiently rapid to respond to climate change, forest management decisions have long-lasting effects [Loehle and LeBlanc, 1996, Lindner, 2000]. Rotation periods, depending on region and tree species, currently range between 80 and 180 years in Central Europe [Lower Saxony Ministry of Food, Agriculture and Consumer Protection, 2014]. Thus, the choice of tree species, rotation period, and forest treatment based solely on past experiences is likely to become inadequate due to new combinations and dynamics of environmental factors and their changes through-out a tree's lifetime [Spittlehouse and Stewart, 2003]. Therefore, new approaches are needed to find optimal forest management strategies.

Several modeling approaches have been employed to assess climate change impacts on forests. For example, (bio-) climatic envelop models [e.g., Box, 1981, Huntley et al., 1995], also known as niche-based, habitat or species distribution models, have been used to project shifts in the potential distribution areas of certain tree species. These models are based on the relationships between a set of climatic variables and observed presence/absence of a species. Kölling et al. [2009] adapted this method to tree species in Germany to support forest practitioners with a preliminary vulnerability estimation and gained large attention [e.g., Ammer et al., 2007, Hanewinkel et al., 2010a, Seiler et al., 2007, Storch and Claussen, 2012]. This method assumes that the current species distribution area defines the adaptation potential based on aggregated climate signals. This approach can be categorized as an indirect impact assessment because aggregated climate signals are used as a proxy to predict future species distributions, and based upon this, assumptions about future production conditions are indirectly derived. Although the method is easy to use, understand, and communicate and exhibits good performance [Kramer et al., 2010] it has been criticized because

it ignores the projected increase in extreme events and does not consider other important factors, such as soil properties [Bolte et al., 2008, Pearson and Dawson, 2003].

Other direct modeling approaches using climate time series at different temporal and spatial scales include dynamic global vegetation models, adaptations of so-called gap models, carbon accounting models, terrestrial biogeochemical models, and individual-tree stand models [cf. Medlyn et al., 2011, for a review]. In addition to models focusing on the description of forest growth and species composition, a number of models describe the effect of single disturbance agents on forests such as storms [e.g., Blennow et al., 2009, Panferov et al., 2009] or insects [e.g., Berec et al., 2013, Jonsson et al., 2011]. However, an obvious gap remains between models intended for understanding systems and scientific advancement and models to answer practical questions. Often scientific models are not sufficiently elaborated to be directly applicable by forest managers. Typically, they provide neither quantifications of possible timber losses nor economic metrics for the assessment of climate change impacts [Hanewinkel et al., 2010b]. Furthermore, they are usually too coarse spatially or temporally to support forest management and forest operations. The Decision Support System-Forest and Climate Change (German: Decision Support System - Wald und Klimawandel, DSS-WuK) attempts to fill this gap [Jansen et al., 2008, Thiele et al., 2009, Thiele and Nuske, 2016]. It provides a scale-independent modeling framework comprising well-established models. The employed models cover various climate change impacts on forests. The quantitative impact description is extended by a risk evaluation and an economic assessment. Although DSS-WuK was parameterized and implemented for the entire area of Germany, we show in this study that the model framework, because of its scale-independent design, can be employed in a spatially explicit manner for individual single forest management units using data with a much finer spatial resolution.

The present study pursues two major goals: (1) to present a model system coupling several submodels that describe the forest-climate interactions: soil and climate, forest growth and productivity, abiotic and biotic hazards and finally the economic valuation; and (2) to demonstrate the model systems' capabilities to provide valuable decision support for forest planning under climate change.

This paper is structured as follows. We start with a detailed description of the modeling system and the coupling of the submodels in the simulation process. We then introduce the 'indicator stand' concept, which is essential to obtain comparable simulation results over the projection periods. The theoretical foundations of the applied submodels are subsequently briefly presented. We then present the case study of Norway spruce in the forest district 'Arnsberger Wald', North Rhine-Westphalia, Germany. We use two climate scenarios to demonstrate the system's capability to project forest development until 2100. For the analysis, the simulation results for the entire period of 2011–2100 are aggregated into three 30-year (climatological) periods, 2011–2040, 2041–2070, 2071–2100, and compared to the reference period 1971–2000. The results are presented in terms of changes in site index, stand characteristics, risks (storm, drought, and insects), and economic measures. We conclude with a discussion of the suitability of the system for its purpose and relate our assessment of climate change impacts to current literature.

II.3.3. Material and methods

Model system

The DSS-WuK [Jansen et al., 2008, Thiele et al., 2009, Thiele and Nuske, 2016] follows the direct impact assessment approach by coupling a number of process-based and statistical submodels describing various aspects of the impact of climate change. It links a climate downscaling model, an individual-tree stand growth and management model, a site index model, a physical soil water model, a physical wind field model, a phenoallometric tree model, and an insect phenology model with damage risk models of windbreak and -throw, lethal drought stress, and pests as well as an economic valuation model. The system functions in a spatially explicit manner at given coordinates using spatial input data for soil, climate, nitrogen deposition, and topography. The spatial resolution of the model is specified by the input data, and thus the system is scale independent. At every considered location, the system simulates a representative stand. Currently, the system can handle only pure stands of one species. We introduce the 'indicator stand' concept, described below, to evaluate the future production conditions of managed stands of Norway spruce. With respect to the temporal scale, the system is implemented to be driven by daily climate data, with submodels exchanging data in a 10-year time interval, and to output results in 30-year climate periods. However, the model is not bound to this temporal resolution.

The various submodels are integrated by defined data input and output interfaces (see Digital Supplement 3). Therefore, the selection of submodels is not fixed but can be changed if the submodel candidate can support the defined data exchange interfaces. It is also possible to extend the system using further submodels, such as additional disturbance agents. The composition of submodels used in this study is presented in Section II.3.3 and described in more detail in Digital Supplement 3.

The central unit of the model framework is a mastermodel (Figure II.10) that defines the orchestration and choreography of the submodels. The mastermodel coordinates the pre-processing of the input data and the control and data flow among the submodels and stores the intermediate and final results to a database. The sub-models exchange data after each coordinating 10-year time step, which is a compromise between complexity and accuracy. The 10-year results are then aggregated for the 30-year periods 1971–2000, 2011–2040, 2041–2070, and 2071–2100. A simulation for one climate scenario runs over the four time periods for each forest stand within the study area.

The simulation starts with the regionalization of ten years of daily climate data to 1-km resolution. The vegetation period is determined separately for every year and forest stand based on regionalized and downscaled local weather data. The climatic water balance and temperature sum within the vegetation period are then modeled simultaneously, and the stand- and soil-dependent rooting depth and distribution as well as a nutrient index value are calculated. From these site conditions, a site index is derived for the growth model. A new indicator stand is generated if necessary, and the leaf area index of the current stand is subsequently computed for the soil water model. The model of drought stress mortality is embedded in the soil water model. Thereafter, the wind damage model is executed, which consists of two parts: the model of the wind load and the damage model. The last risk model is the biotic model, which, again, contains two models: a phenological model predicting the number of bark beetle generations per year and a damage model. The final model in every time step is the stand growth model. Stand growth is projected based on the site index

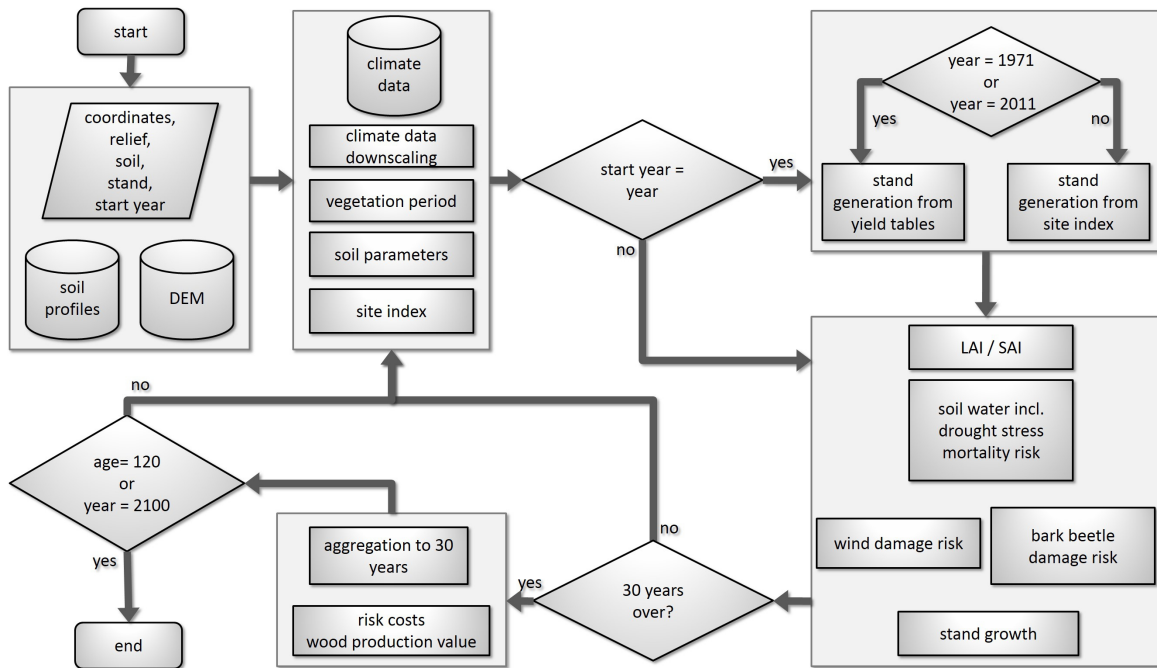


Figure II.10.: Schema of the mastermodel controlling the coupled submodels, showing the process flow beginning at top left (start) and ending at bottom left (end).

estimated by the climate-sensitive site index model. If the last period or the maximum stand age (120 years) is not reached, this loop continues, and another ten years are modeled. If the simulation time is complete, we leave the loop and aggregate the collected 10-year results to 30-year periods, as recommended by the usage notes of the regional climate model [DKRZ, 2007]. Aggregation of the site index is straightforward using an arithmetic mean. Risks of damage are described by the conditional probability that a stand, that survived until a certain age drops out at this age. The risk of damage within a period of 30 years is calculated separately for drought, storms and insects by the following:

$$Risk_{30} = 1 - (1 - Risk_{1-10}) \times (1 - Risk_{11-20}) \times (1 - Risk_{21-30}) \quad (II.3)$$

where $1 - Risk$ provides the conditional survival probability, which is the complement of the conditional drop-out probability [(cf. Staupendahl, 2011)]. The three resulting risk values are combined in the same way to obtain the total risk in a period. The total conditional probability that a stand that survived until the beginning of the period still exists at the end of the period is then one minus the total risk. The 30-year results were used as input in the economic model calculating the contribution margin of timber production and the risk costs. After completing this process, all results are written to the database for further analysis.

Indicator stand concept

Because we are striving to extract the climate effect on forest productivity and on potential risk factors, we use exemplary spruce stands ('indicator stands') of the age classes 30 to <60, 60 to <90 and 90 to <120 years for each time period (Figure II.11) instead of the stands' actual stocking information. We create imaginary pure Norway spruce stands for all

forest inventory polygons of the study area. However, the stand characteristics depend on the specific site conditions at the respective location and time of creation. Stand generation is carried out using the site index model and the stand generator of the employed individual-tree stand growth and management simulator. Because we are striving to extract the climate effect on forest productivity and on potential risk factors, we use exemplary spruce stands ('indicator stands') of the age classes 30 to <60, 60 to <90 and 90 to <120 years for each time period (Figure II.11) instead of the stands' actual stocking information. We create imaginary pure Norway spruce stands for all forest inventory polygons of the study area. However, the stand characteristics depend on the specific site conditions at the respective location and time of creation. Stand generation is carried out using the site index model and the stand generator of the employed individual-tree stand growth and management simulator.

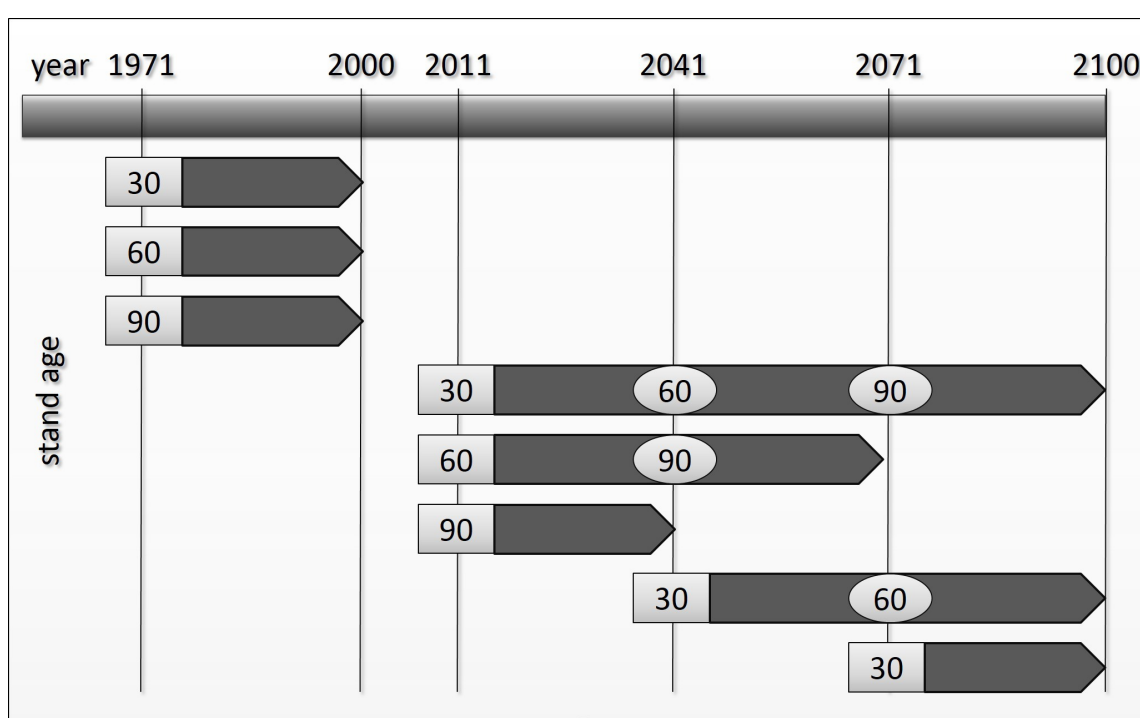


Figure II.11.: Indicator stand concept covering the four simulated time periods. The rectangles at the beginning of arrows symbolize newly generated stands with their respective ages. The ellipses give the ages of the continued stands at the beginning of the subsequent periods.

Once generated, the stand grows under the conditions of the applied climate scenario and passes over into the next period, e.g., a stand of age class 30–60 years becomes the 'indicator stand' of the age class 60–90 years in the following period, and a stand of age class 60–90 becomes the 'indicator stand' of the age class 90–120 years. Thus, the climate history of a stand and, therefore, its realized growth depending on ever-changing site-indices and stand structure are taken into account.

This approach permits an evaluation of the effects of climate on tree growth and risks at different development stages (tree ages) by comparing the results of the climate period of the past with the results for the projection periods.

Description of the submodels

The submodels are versions of established and validated models adapted to the purpose of this model system. Therefore, we present only the general outline of each submodel, our adjustments, and the reference to the publication containing the original model description. Fact sheets, including the input and output variables of each submodel indicating the data exchange of the submodels as well as their influence is provided in Digital Supplement 3.

Regionalization of climate

The regionalization of climate data is performed using the modified SVAT-Regio model by Olchev et al. [2008], which is based on the Kriging method [Cressie, 1993]. The variables are scaled down from a resolution of 0.2° to 1 km. The regionalization is based on climate data of 3×3 CLM grid cells. Depending on the variable, different factors are used for the regionalization, such as elevation differences, relief characteristics, wind direction, and distances to measuring stations.

Phenological and allometric models

Due to an extended vegetation period as a result of changing climate conditions, we expect a changing phenology of the trees. Therefore, we calculate the vegetation period for each year separately. The start and end dates of the vegetation period are determined using climate-dependent functions by Menzel [1997], Menzel and Fabian [1999], Wilpert [1990].

Following Sogachev et al. [2011], we estimate the leaf area index (LAI) with the model by Law et al. [2001] in combination with the litterfall model from Ahrends et al. [2010]. The calculated maximum value is modified by the seasonal variation induced by the vegetation period model [Hammel and Kennel, 2001].

For estimating the effective rooting depth, a proxy of the maximal depth for water and nutrient uptake, the rules by Czajkowski et al. [2009] based on tree species, soil texture, tree age and annual precipitation sum are applied.

Nutrient index

The site index model from Albert and Schmidt [2010] requires information about soil nutrient classes from site mapping, which is a classification method based on physical and chemical soil properties. To estimate these classes, we parameterize a multiple linear regression model with soil profiles from the first National Forest Soil Inventory in Lower Saxony [Bartens and Büttner, 1997] and soil profiles from Eberl [1998]. Examples of such regression models can be found in Albert et al. [2016], Suttmöller et al. [2013].

Soil water modeling

For modeling the soil water balance, we use the detailed, process-based one-dimensional Soil-Vegetation-Atmosphere Transfer Model BROOK90 by Federer et al. [2003]. In BROOK90, soil water transport is described by the Darcy-Richard equation with daily resolution. Soil water fluxes, parameters of the water retention curve and hydraulic conductivity function are deduced from soil texture using the pedotransfer function of Clapp and Hornberger [1978] for each horizon. Since the values for porosity are too low for most forest

soils, we use the correction by Federer et al. [1993]. Soil texture classification is carried out using the Triangle software [Gerakis and Baer, 1999]. Because BROOK90 uses the water potential of the top layer to estimate soil evaporation, large differences in the estimated thickness of the first soil horizon affect the ratio of soil evaporation to transpiration. Therefore, we add a 5 cm humus layer to all soil profiles, as no information on humus layer is provided in the available soil map (BK 1:50,000), and parameterize the forest floor with the hydraulic parameters for peat [Lee and Pielke, 1992].

Model of drought stress mortality

To estimate drought stress mortality, we employ the critical limits concept from air pollutant monitoring. Following Czajkowski et al. [2009], a critical limit of plant water status occurs when cavitations in tree xylem lower the (stem) xylem conductivity considerably. The surviving trees after an event with exceeded critical limits are quantified as a share of the total stand, which is a function of the number of days with exceeded critical limits of soil water availability. We describe the relationship of the critical limits of soil water availability with tree mortality using a Weibull-function [cf. Linton et al., 1998].

Wind damage model

The site-dependent wind load is calculated using a modified version of the three dimensional boundary layer model SCADIS [Sogachev et al., 2002, Sogachev and Panferov, 2006, Panferov and Sogachev, 2008]. The model calculates the three-dimensional wind field and turbulent kinetic energy for complex landscapes, considering structural information of different vegetation types. Therefore, it is able to estimate the mean- and gust-wind loads on trees taking into account stand characteristics such as height, LAI, and crown closure, delivered by the forest growth submodel. The estimation of wind damage also implements the critical limit approach. A windthrow or windbreak event occurs after one of the critical limits of wind load is exceeded, either for throw or for break. The critical level of a windthrow event is a function of the tree anchorage, which is determined by the soil moisture content calculated by the soil water model and the soil temperature. The critical level for stem break is a function of stem properties, i.e., the modulus of rupture. The conditional drop-out probability is then calculated depending on the wind load as described by Panferov et al. [2009].

Bark beetle damage model

To calculate damage, we first estimate the number of bark beetle (*Ips typographus*) generations per year using the model PHENIPS Baier et al. [2007]. The modeling approach is based on triggering different phenomenological stages of bark beetles by the thermal sums of daily mean and maximal temperature (in degree-days). The conditional drop-out probability of a stand is then calculated depending on the number of beetle generations per year, the soil moisture calculated by the soil water model, the stand age, and the basal area of the stand using the model of Seidl et al. [2007] calibrated with data from Saxony-Anhalt State Forest.

Site-index model

The climate sensitive site index is estimated by the statistical model of Albert and Schmidt [2012, 2010] fitted to data from the German National Forest Inventory I and II and the inventory plots of the Lower Saxon State Forest. The site index is given as the theoretical mean stand height in meters of a forest at age 100 years and growing under assumed fixed site conditions. The Generalized Additive Model uses the explanatory variables nutrient class, available soil moisture, nitrogen deposition, mean temperature in the vegetation period, and mean climatic water balance in the vegetation period as well as the geographic coordinates. The effect of non-lethal drought is also accounted for as the model projects a significant reduction of the site index as a function of decreasing climatic water balance.

Forest growth model

To model the growth of the forest stands, we employ the statistical individual-tree stand growth and management model TreeGrOSS parameterized for northwestern Germany [Nagel, 2011, Döbbeler et al., 2002]. TreeGrOSS is the core for several forest simulation systems, such as the Decision Support Systems 'BWinPro' and 'Waldplaner 2.0'. Both are used for operational silvicultural planning, for instance, in Northwest Germany [Böckmann, 2016]. Usually a 5-year update interval is used in simulations. The site index in TreeGrOSS is updated with new values from the site index model in step with the coordinating time intervals of the master model (10 years), and thus the growth rate changes every ten years and is applied to the current tree status. We choose crop tree selection with selective thinning and subsequent harvesting by target diameter following the management rules of the Federal State of Lower Saxony Niedersächsische Landesforsten [2011] as the management strategy for all stands. Growth and harvesting is not carried out if it results in less than 200 stems per hectare, which is defined as the end use criterion of a stand. In this case, the stand is fixed to its last condition, and risks are simulated accordingly to obtain full time series and avoid compromising the 'indicator stands' concept.

Economic model

The aim of the economic model is to express both the various risks and the growth potential using a single economic indicator. For this purpose, for each age class, the mean annual contribution margin of timber production within the particular period is calculated. The difference between this value and the corresponding periodic annual contribution margin without consideration of risk is interpreted as risk costs.

The mean annual contribution margin is calculated for each 5-year step within the period by the felling value at this age plus the contribution margins and costs, respectively, of all intermediate harvesting and tending operations within the period up to that age, minus the felling value at the beginning of the period. The probability that the stand drops out at that age and therefore that the corresponding mean annual contribution margin is realized depends on the risk. Thus, there is a distribution of mean annual contribution margins, and its expected value is then calculated as a weighted mean [cf. Staupendahl and Möhring, 2011]. The weights are derived by a linear survival function defined by the points $(t_1, 1.0)$ and (t_2, s) , where t_1 and t_2 denote the ages at the beginning and the end of the period and s gives the probability that the indicator stand survives the period.

The volume of the remaining and removed stand at the timesteps are provided by the forest growth model described above; the cost and revenue models are derived from accounting data of the Lower Saxony State Forest and the work of Rüping [2009].

Analysis of results

All statistical analysis and plots were performed using the statistical software R [R Core Team, 2015] in combination with the packages ggplot2 [Wickham, 2009], sp [Bivand et al., 2013], rgdal [Bivand et al., 2015], maptools [Bivand and Lewin-Koh, 2015], lattice [Sarkar, 2008], RColorBrewer [Neuwirth, 2014], RPostgreSQL [Conway et al., 2013], reshape2 [Wickham, 2007], and plyr [Wickham, 2011]. Correlation analysis were carried out using Kendall rank correlation coefficient with a non-parametric tautest for statistical dependence. Distribution comparisons were performed using the non-parametric two-sample Kolmogorov-Smirnoff test.

Input data

The DSS-WuK needs a set of input data on the considered forest stands that includes soil properties, local topography, nitrogen deposition, and climate characteristics. The locations of the 462 stands are represented by their centers of mass (centroids). The simulations are run for each centroid. The topography and the soil characteristics are assumed to be static over the considered time, whereas the climate and nitrogen deposition are time series derived from scenarios of future development.

Soil

Soil properties (soil texture, bulk density, stone content, organic matter, available soil water capacity, etc.) were taken from a digital soil map of scale 1:50,000 (BK 50, source: Geological Service North Rhine-Westphalia) resulting in 289 potentially unique values for the 462 stands. The potential cation exchange capacity was calculated with pedotransfer functions of Müller and Waldeck [2011].

Topography

The elevation, slope, and aspect were derived from a 90 m resolution digital elevation model based on the Shuttle Radar Topography Mission (SRTM) dataset Version 4 edited by the CIGAR Consortium for Spatial Information [Jarvis et al., 2008].

Nitrogen deposition

Long-term trends for the deposition of nitrogen were calculated with the model MAKEDEP [Alveteg et al., 1998] as described by Albert and Schmidt [2010]; Hauck et al. [2012]. The model was run with grid-based estimates of Gauger et al. [2008] for a period from 1995 to 2004. To reconstruct the deposition before 1995, we used the regional trend from the EMEP database [Tarrasón and Nyíri, 2008] and standard time series from Alveteg et al. [1998]. From 2004 onward, the annual nitrogen deposition was maintained constant. Mapping the nitrogen deposition grid of 1-km spatial resolution to the centroids of the stand polygons resulted in 141 unique grid points in the study area.

Climate

We employed the climate scenario 20C3M for the period 1971–2000 (reference) and SRES B1 and A1B [IPCC, 2000] for the projection period 2011–2100 modeled by coupled AOGCM ECHAM-5-MPIOM (run 1), regionalized with the RCM Climate-Local-Model [CLM; Hollweg et al., 2008] and interpolated to a spatial resolution of 0.2° [Datastream 3, Lautenschlager et al., 2009a,b]. Data with a daily timestep were used, i.e., the daily sum of precipitation and solar radiation, daily means for temperature, vapor pressure, and wind speed, and daily extreme values of maximal and minimal temperature and maximal wind gust. The data were further statistically downscaled (see Section 2.3.1) taking into account the elevation and the exposition of the slopes. The downscaling resulted in 458 potentially different climate time series mapped to the centroids of the stands within the study area. The climate data were then bias corrected using the observation data of the German Weather Service (German: Deutscher Wetterdienst, DWD), and the delta-change and linear transfer functions of Mudelsee et al. [2010] and considering plausible conditions such as $T_{min} < T_{mean} < T_{max}$. The vapor pressure was adjusted to bias-corrected temperatures.

Site description

The forest district 'Arnsberger Wald' with a size of approximately 10,000 ha is located in the northern part of the Rhenish Massif, which is in the western part of Germany (cf. Figure II.12). It is characterized by the bends of the river Ruhr. The dominant tree species (45%) is Norway spruce (*Picea abies* (L.) H. Karst.). Other species are European beech (34%), Oak (7%), Scots pine (1%), other deciduous wood (8%) and other coniferous wood [5%; Wald und Holz NRW, 2016]. Since Norway spruce is by far the most economically important species in the 'Arnsberger Wald', the presented case study focuses exclusively on Norway spruce.

The terrain is dominated by steep slopes with elevations ranging between 200 and 550 m a.s.l. The northwest is generally lower than the southeast (Figure II.12). The forests are located on the higher grounds covering hill tops and slopes. Depending on the elevation, the current annual mean temperature decreases from +9°C in the northwest to +6.4°C in the higher southeast. By contrast, the annual precipitation increases with height from 850 mm in the north-western to 1100 mm in the hilly south-eastern regions. The study area is dominated by shallow soils with available soil water capacity in the rooting zone below 120 mm in the south and above 200 mm for deeper soils in the north. Due to various geological substrates and relief intensities, the spatial heterogeneity of the soils is high, and adjacent areas might have very different properties.

II.3.4. Results

Climate change

In the following, we summarize the main results of the downscaling model driven by bias-corrected daily climate data (C20, B1, A1B) in the regional climate model CLM. Visualizations are provided in Digital Supplement 4. The target grid resolution is 1 km², and the temporal resolution is 1 day.

The annual mean temperature averaged over 30-year periods is projected to increase in scenario B1 and A1 B by 2.0 and 2.9°C, respectively, from 1971–2000 to 2071–2100 in

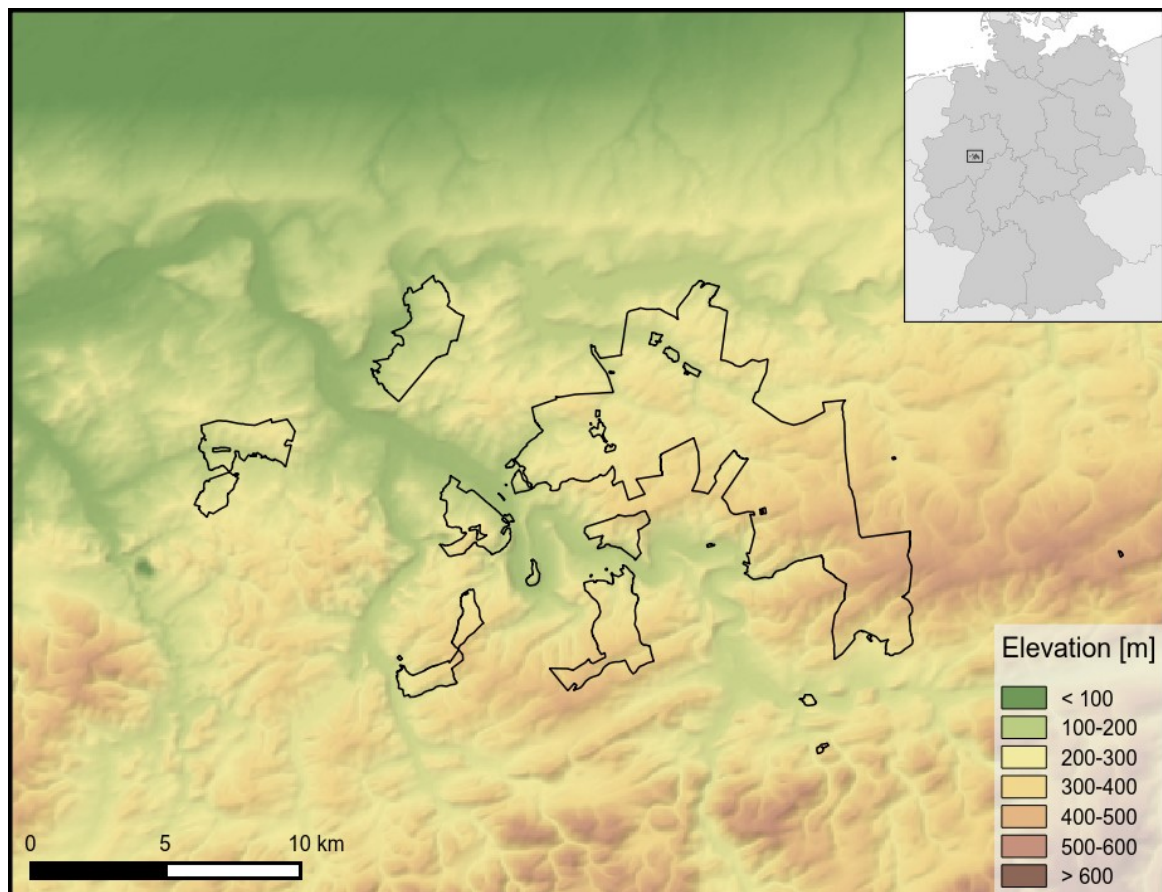


Figure II.12.: Location of the study area 'Arnsberger Wald' (black polygons, 51.3°–51.5°N and 7.8°–8.4°W) derived from the forest inventory map depicted with the elevation of the surrounding landscape based on SRTM data [Jarvis et al., 2008].

the study area. An increase in the total annual precipitation of rather small magnitude is projected: 4.2% (B1) and 3% (A1B) from 1971–2000 to 2071–2100.

The climatic water balance of the vegetation period using evapotranspiration of a hypothetical grass reference crop [Allen et al., 1998] is an input parameter of the site index model [Albert and Schmidt, 2010] and an indicator for drought stress [cf. Albert et al., 2016]. The 30-year average of climatic water balance of vegetation period shows a strong decrease toward the end of the 21st century. The average climatic water balance over all forest stands decreases by 31 mm (24%) in scenario B1 and 71 mm (55%) in scenario A1B from 1971–2000 to 2071–2100. Furthermore, the mean sum of hot days, i.e., days with a daily maximum temperature above 30°C, increases from 161 during the 30-year reference period to 380 days in scenario B1 and 577 days in scenario A1B in the period 2071–2100. In summary, the water supply deteriorates over time, and the sum of drought events, i.e., a year with a negative climatic water balance in a forest stand, increases from 464 events in the reference period to 559, 2019, 2362 events in the projection periods under climate scenario B1 and 1790, 2946, and 4260 events under climate scenario A1B.

The mean number of days with storm events, i.e., days with maximum wind speed above 20.8 m/s at 10 m height, increases from 83 for the first 30-year period to 110 (B1) and 147 (A1B) days during 2071–2100. The variation between the different forest stands is rather small. A similar pattern but with less events and higher spatial variation is observed for heavy storm events, i.e., days with maximum wind speed above 24.5 m/s. The mean number of days with heavy storm events in 30 years increases from 4 days in the reference period to 8 (B1) and 14 (A1B) days in the last period.

This analysis provides a basic overview of the general climate trends in the region. A more thorough examination of the interannual climate dynamics at a specific forest stand is revealing. In the last period, the highest monthly mean temperature averaged over 30 years coincides in time with the lowest precipitation sum in scenario A1B. Furthermore, analyzing the changes not only in 30-year periods but on an annual scale reveals years of disruption of the general trend of increasing temperatures and precipitation sums. Although the number of dry years increases over time, the increase in temperature at annual resolution is not monotone.

The effects of these changes on the site index, stand characteristics, risks, and aggregated economic measures are evaluated in this simulation experiment. The results are presented in the following.

Changes in growth potential

In our simulation, we found an increase in the site index (growth potential of forest sites) during the 21st century, with a slight initial decline in scenario B1 in the period 2011–2040 (Figure II.13). The site index increases by 17% (B1) and 25% (A1B) from the reference to the last period (2071–2100). The differences in growing capacity between the climate periods are statistically significant for both climate scenarios, with the exception of the first projection period compared to the reference period in scenario B1 (two-sample Kolmogorov-Smirnov test, two-sided alternative hypothesis: for all 30-year periods with $\alpha = 5\%$).

Figure II.14 shows the spatial distribution of the site indices for the considered periods for scenario A1B as an example. The influence of the relief (cf. Figure II.12) and associated temperature gradient are clearly visible throughout all periods: the higher the elevation, the lower the site index. This general pattern remains unchanged overtime, although the

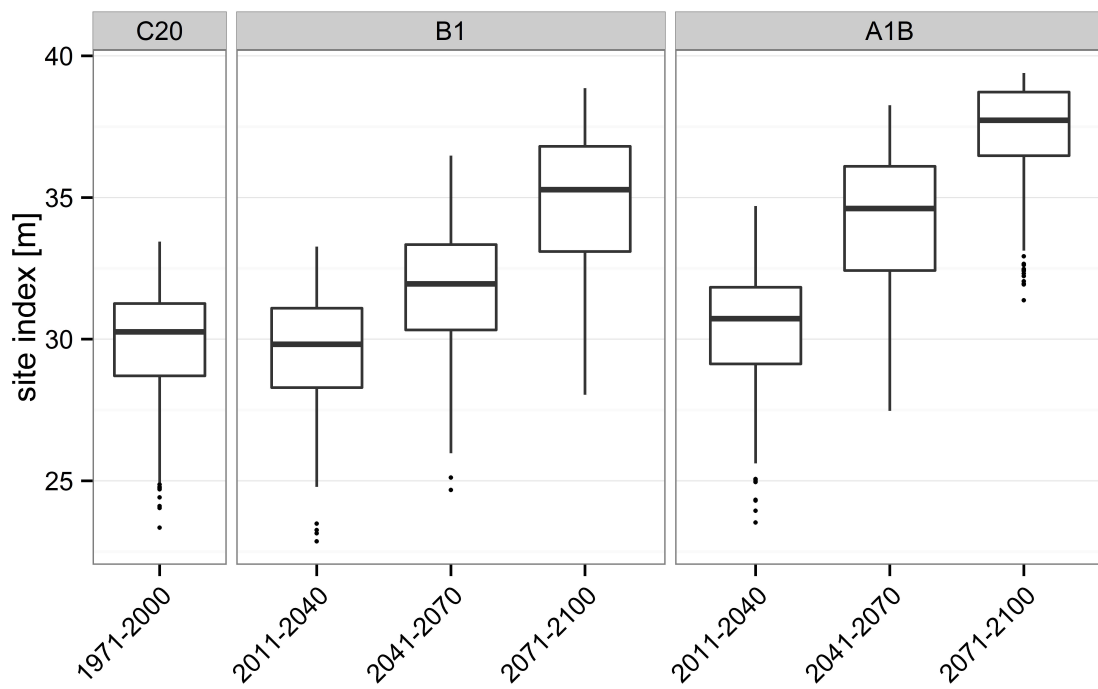


Figure II.13.: Box-and-Whisker plots (median, 25th and 75th percentile, 1.5 interquartile range, outliers) of the site index for climate periods of the C20 reference and two climate scenarios B1 and A1B.

differences gradually diminish under the A1B scenario, and the different inventory areas become more homogeneous with respect to their site indices. This effect is also reflected by the decreasing correlation between the site index and the elevation toward the end of the century under scenario A1B (for 1971–2000: Kendall's tau = -0.67*, for 2071–2100: -0.45*, * significant at $\alpha = 5\%$). Under the B1 scenario, this correlation remains unchanged.

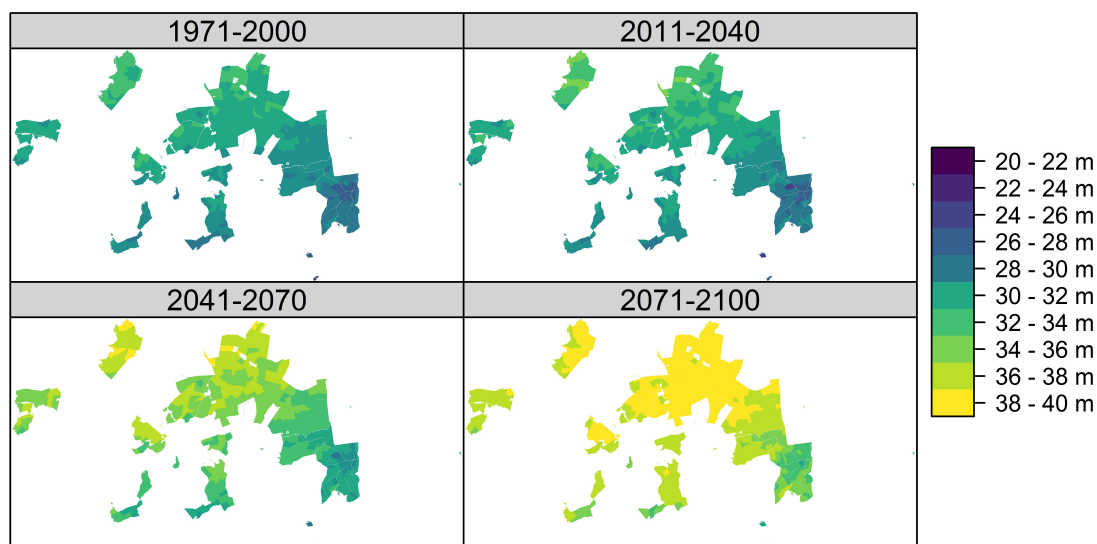


Figure II.14.: Maps of the site indices [m] of climate scenario A1B (and C20 reference).

Stand characteristics

The predicted stand characteristics for each age class (indicator stands), climate period, and both climate scenarios are shown in Table II.8. For the age class 30–60 years, we find an increase in the quadratic mean diameter (Dq) and height of trees with the quadratic mean diameter (Hq) along the climate periods concurrent with a reduced stem number. The relative increase in diameter is 20% (B1) and 26% (A1B), and the increase in height for this age class is 24% (B1) and 37% (A1B). For the age class 60–90 years, we also find an increase in diameter and height between the reference and the last climate period combined with a decreasing stem number and basal area. The Dq of the oldest age class remains relatively constant over time due to target diameter thinning carried out by the stand growth model. Simultaneously, the number of stems, the height, and the basal area decrease over time because the target diameter is reached earlier (cf. Table II.9). The forest management phase 'end use' is initiated if the next target diameter thinning would result in less than 200 stems per hectare.

Table II.8.: Stand characteristics at the end of the 30-year simulation periods for each age class and climate scenario (B1, A1B; as a common reference, C20 is printed in the middle of both scenario columns) averaged over all 462 stands. Dq: quadratic mean diameter of trunks, Hq: height of trees with the quadratic mean diameter, BA: basal area is the total cross-sectional area of stems in a stand measured at breast height.

Age class [years]	Climate period [years]	Stems/ha [N]		Dq [cm]		Hq [m]		BA [m^2 /ha]	
		B1	A1B	B1	A1B	B1	A1B	B1	A1B
30-60	1971-2000		786	24.5	24.5	15.8	15.8	34.6	34.3
	2011-2040	795	800	24.5	24.5	15.8	15.8	34.6	34.7
	2041-2070	681	653	27.8	28.5	17.8	18.5	37.3	38.7
60-90	2071-2100	634	636	29.5	30.9	19.6	21.6	41.2	45.9
	1971-2000		376	37.8	37.8	24.8	24.8	41.5	41.5
	2011-2040	375	375	37.8	37.8	24.7	24.7	41.4	41.4
90-120	2041-2070	319	322	39.1	39.0	24.1	24.3	37.1	37.4
	2071-2100	288	284	42.3	42.9	26.0	26.9	38.9	39.9
	1971-2000		268	45.1	45.1	29.5	29.5	42.6	42.6
	2011-2040	269	270	45.1	45.1	29.5	29.5	42.8	42.9
	2041-2070	239	229	45.6	45.7	28.4	28.7	39.2	37.6
	2071-2100	227	234	45.1	45.0	27.0	27.3	36.1	37.2

Table II.9.: Age when stands reach the end use phase. The minimum, maximum and mean stand ages of all 462 stands for both climate scenarios (B1, A1B; as a common reference, C20 is printed in the middle of both scenario columns).

Climate period	min. age [years]		mean age [years]		max. age [years]	
	B1	A1B	B1	A1B	B1	A1B
1971-2000	105		106		110	
2011-2040	105	105	105	105	110	110
2041-2070	85	85	93	93	100	100
2071-2100	85	85	89	89	90	95

Changes in damage risks

Drought-induced tree mortality risk As mentioned in the model description, drought-induced mortality should not be confused with drought stress leading to, for example, reduced growth. Tree death due to water shortage is a very rare phenomenon in the study area (cf. Table II.10). The model estimates at least some drought stress mortality in the projection periods. In particular, in the period 2041–2070, which features very hot and dry summers, the drought-induced conditional drop-out probabilities increase sharply on some sites. Although most of the conditional drop-out probabilities are rather small, the highest values are 0.48 (B1) and 0.63 (A1B). The drought stress affects areas where the available soil water capacity in the rooting zone is extremely low (less than 110 mm).

Table II.10.: Number of forest stands (N = 462) where drought stress mortality, i.e., drop-out probability > 0, occurs depending on age class, climate period and climate scenario (B1, A1B; as a common reference, C20 is printed in the middle of both scenario columns).

Climate period	Age class					
	30-60		60-90		90-120	
	B1	A1B	B1	A1B	B1	A1B
1971-2000	0		0		0	
2011-2040	0	3	0	1	0	3
2041-2070	2	26	1	16	0	30
2071-2100	77	4	57	4	21	4

We find a negative correlation between the drop-out probability caused by drought stress mortality and the available soil water content, meaning the lower the water content, the higher the risk of drought stress mortality event due to long durations of drought (Kendall's tau = -0.52* over all age classes for period 2071–2100 with climate scenario B1; Kendall's tau = -0.35* over all age classes for period 2041–2070 with climate scenario A1B; * significant at $\alpha = 5\%$).

Bark beetle damage risk According to the results of the bark beetle damage risk model, damage is expected only in the older age classes (cf. Figure II.15) because, in the employed

model, bark beetles attack only trees older than 60 years. For both climate scenarios, we observe a monotone increase of the bark beetle-induced drop-out probability over the periods with a higher level in the age class 90–120 years due to stand-dependent damage predisposition. This increase results in a mean conditional drop-out probability of 0.09 (B1) and 0.1 (A1B) for the oldest age class in the last 30-year period. The drop-out probability increases by a factor of 1.5 (B1) and 1.7 (A1B) from the reference to the last climate period. The differences in damage probabilities between the reference period and all climate periods of both climate scenarios are statistically significant for both age classes, 60–90 and 90–120 years (two-sample Kolmogorov-Smirnov test, two-sided alternative hypothesis: for all 30-year periods and age classes 60–90 and 90–120 years with $\alpha = 5\%$).

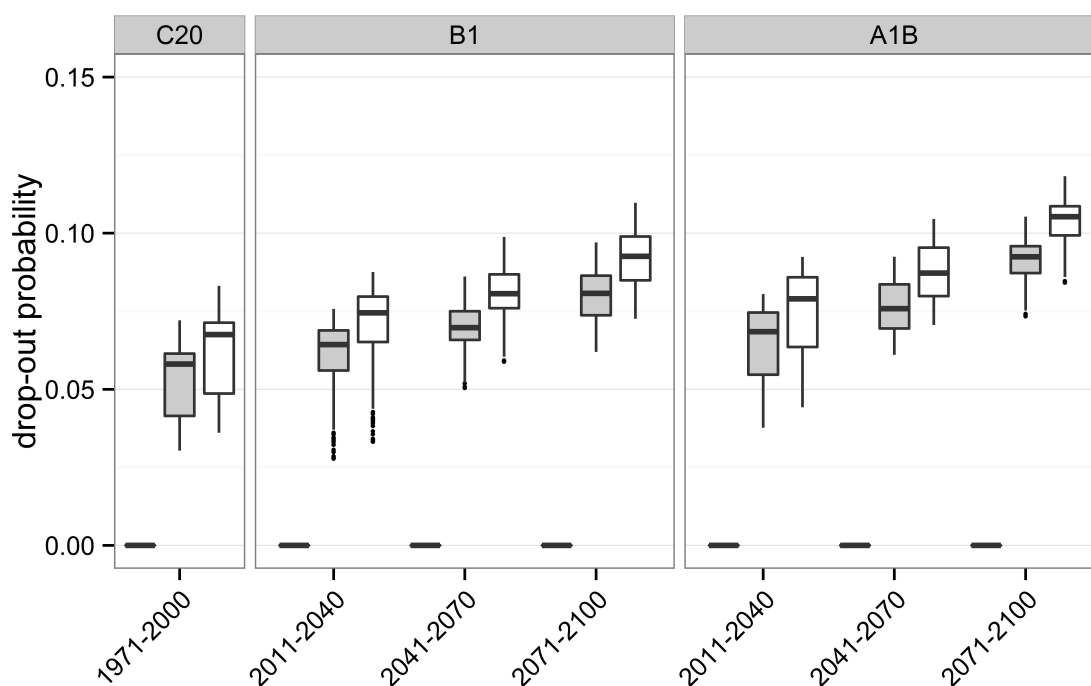


Figure II.15.: Box-and-Whisker plots (median, 25th and 75th percentile, 1.5 interquartile range, outliers) of the bark beetle given as the drop-out probability depending on stand age class and climate period for the C20 reference and two climate scenarios B1 and A1B. Dark gray: age class 30–60 years; light gray: age class 60–90 years; white: age class 90–120 years.

The lower northern part of the study area is more vulnerable to bark beetle infestations than the hilly southern parts (see Digital Supplement 4). This pattern is identical for the stand age classes 60–90 and 90–120 years. The negative correlation between elevation and bark beetle damage risk is significant in the period 2071–2100 (for age class 60–90 years: Kendall's tau = -0.81^* (B1) and -0.81^* (A1B); for age class 90–120 years: -0.81^* (B1) and -0.80^* (A1B); * significant at $\alpha = 5\%$).

Wind damage risk Wind damage includes drop-out probabilities due to windthrow and windbreak of trees (Figure II.16). In the reference period (1971–2000) as well as in the period 2041–2070 with climate scenario B1, the damage risk is significantly higher for younger stands. The same applies for the period 2011–2040 with climate scenario A1B. During the period 2071–2100, the risk for old stands is notably higher than for young- and mid-aged ones for both climate scenarios (for the spatial pattern, see Digital Supplement 4). The damage risk differences are significant between the periods for all age classes in both climate scenarios (two-sample Kolmogorov-Smirnov test, two-sided alternative hypothesis: for all 30-year periods and age classes with $\alpha = 5\%$). Starting with conditional drop-out probability levels in the reference period (1971–2000) of less than 0.1 on average over all forest stands, the risk of wind damage increases by factors of 2.8 (B1) and 3.1 (A1B) in the 90–120 year age class in the last period. Under the climate scenario B1, the risk for all age classes increases from the reference to the first projection period and decreases in the second projection period before it reaches its maximum in the last period. Under climate scenario A1B, the risk increases for the young- and mid-age classes from the reference over the first to the second projection period and then remains relatively unchanged in the last period. For old stands (age class 90–120), the pattern is different, and the wind damage risk also increases in the last period. For both climate scenarios and all age classes, there is a strong increase in the interquartile range, i.e., spatial heterogeneity, over the climate periods. For climate scenario B1, this increase is especially notable in the last period, whereas for the climate scenario A1B, the interquartile range increases considerably between the first and the last two projection periods.

Economic valuation

The risk costs indicate the economic effect of aggregated biotic and abiotic damage risks and how it changes over time. In addition, the annual contribution margin of timber production summarizes positive climatic effects caused by an enhanced volume increment and the negative economic effects due to increased costs of damages.

Figure II.17 (top) shows that the range of risk costs among the different forest stands increases strongly over time under both climate scenarios (for the spatial pattern, see Digital Supplement 4). This effect also increases with age class and is relatively low for young stands and largest for old stands, except for period 2041–2070 under climate scenario B1. The risk costs of all projection periods differ significantly from the risk costs of the reference period as well as between all age classes under both climate scenarios (two-sample Kolmogorov-Smirnov test, two-sided alternative hypothesis: for all 30-year periods and age classes with $\alpha = 5\%$). We find an increase in the mean annual contribution margin over time for the first two age classes under both climate scenarios, except a slight decrease in the first B1 projection period (cf. Figure II.17, bottom). For the oldest age class, we note a small decrease when comparing the projection periods with the reference period. However, the mean annual contribution margin remains positive. The differences between all climate periods are statistically significant for all age classes under both climate scenarios except between the reference period and the first B1 projection period (two-sample Kolmogorov-Smirnov test, two-sided alternative hypothesis: for all 30-year periods and age classes with $\alpha = 5\%$).

Notably, the mean annual contribution margin remains relatively stable or even increases over the three periods, although risk costs are simultaneously increasing significantly.

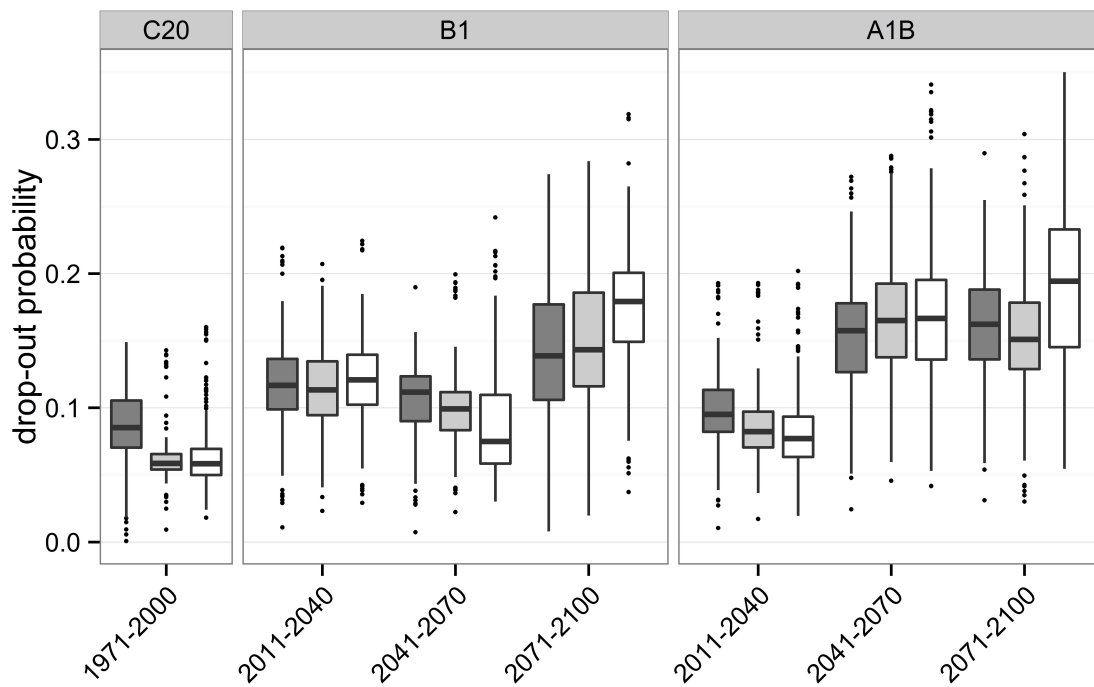


Figure II.16.: Box-and-Whisker plots (median, 25th and 75th percentile, 1.5 interquartile range, outliers) of the wind damage risk given as the drop-out probability depending on stand age class and climate period for the C20 reference and two climate scenarios B1 and A1B. Dark gray: age class 30–60 years; light gray: age class 60–90 years; white: age class 90–120 years.

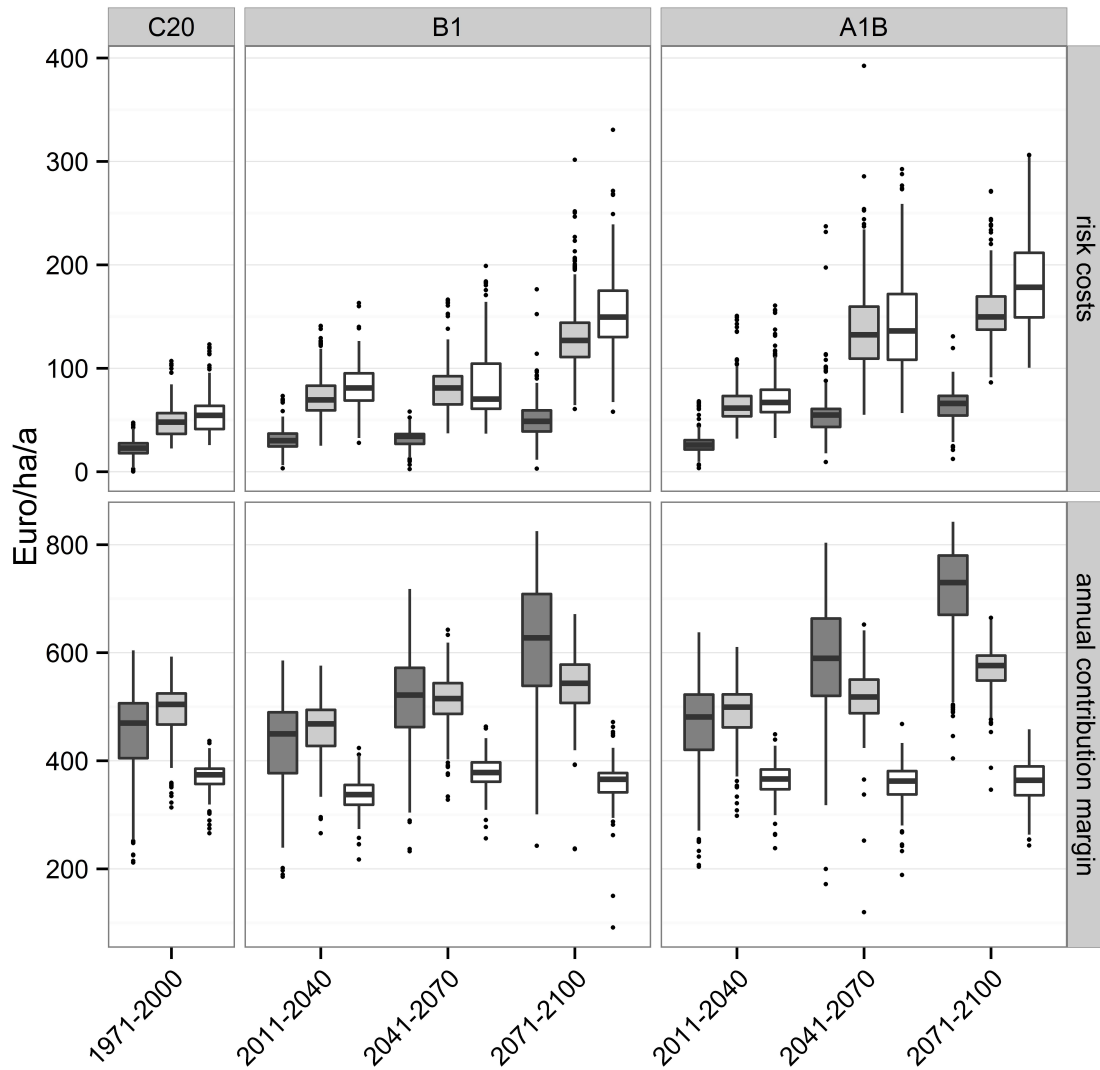


Figure II.17.: Box-and-Whisker plots (median, 25th and 75th percentile, 1.5 interquartile range, outliers) of the risk costs (top) and the mean annual contribution margin of timber production under consideration of risks costs (bottom) both depending on stand age class and climate period for the C20 reference and two climate scenarios B1 and A1B. Dark gray: age class 30–60 years; light gray: age class 60–90 years; white: age class 90–120 years.

II.3.5. Discussion

The discussion is divided into three main sections: (1) the design and implementation of a complex dynamic model system; (2) the critical evaluation of submodels; (3) the assessment of the impact of climate change on forest growth and risk.

Design and implementation of a complex dynamic model system

In the present study, we have demonstrated that it is possible to build a complex model system covering forest growth, damage risk evaluation, and economic assessment under climate change. The model system comprises various established and validated process-based and statistical models driven by temporal high-resolution climate data. Using this direct impact assessment approach, the system is able to quantify the impacts of climate change, in contrast to indirect methods, which deliver only qualitative measures of vulnerabilities. The analysis of the interannual variability of the projected climate indicates that it is very important to model the entire timespan, as performed in this study, to adequately evaluate the future growth conditions of forests. The comparison of merely two points in time with different growth conditions and ignoring the dynamic changes in between is not advisable for damage risk evaluation. Thus, climate change has to be viewed as a complex process and not just as a new state of environmental conditions that immediately drops in, as performed, for example, by Asche [2009].

Forests are, in contrast to agricultural systems, long-lasting: several processes run for long periods of time using different stores, e.g., soil for water and nutrients or biomass for carbon storage. Only dynamic simulations driven by time series of climate data can incorporate the dynamics of these stores and are therefore the appropriate modeling approach to quantify climate change impacts on scales of operational forest management. Using such a dynamic simulation system in combination with the concept of 'indicator stands' (cf. Subsection 2.2), we have been able to quantify the age-dependent differences in climate change impacts on forests at stand level. The indicator stand concept enables climate effects to be separated from age-dependent effects on growth and damage risks while retaining feedback between changing stand characteristics and biotic as well as abiotic risks. Therefore, we have been able to trace the impacts of climate change on the given sites overtime. Indicator stands in the same location with identical stand age classes permits the separation of climate effects from growth and location effects.

We based our impact assessment on two climate scenarios (B1 and A1B) to demonstrate the model system's capabilities. To obtain more robust estimations for thorough decision support, the analysis of climate impacts on forest stands should be based on ensembles of multiple and, where possible, fundamentally different climate scenarios [Moss et al., 2008].

Some risks are not always inherently lethal but increase the vulnerability to other risks. Some of these feedbacks are currently present in the model system, e.g., drought stress increases the vulnerability to bark beetle attacks, but, for example, feedbacks between vegetation and climate, which could be relevant, are not taken into account [Bonan, 2008, Tölle et al., 2014]. However, including the interaction of vegetation and climate would increase the complexity enormously by requiring climate models to be run in parallel. Moreover, genetic variations can lead to varying responses to changing climate conditions. We used an 'average' Norway spruce, although one adaptation strategy to climate change is to establish different genotypes, e.g., seeds from regions facing the projected climate already today

[e.g., Spittlehouse and Stewart, 2003]. Such genetic or provenance adaptations are not yet implemented explicitly but can be realized by different parameterizations of tree species.

Although the model system comprises many established and validated models such as the soil water model and the growth model, some of the damage risk models were developed especially for this model system and are difficult to parameterize. In combination with uncertainties in the input data, particularly with regard to climate projections, these uncertainties accumulate along a cascade [Schneider, 1983, Reyer, 2013]. Further research to improve the input data as well as the impact models is necessary to reduce those uncertainties. However, for the mastermodel, we chose a modular design that permits the replacement of any submodel by a different implementation that uses the same interface. We used specialized programming techniques to bind submodels of different programming languages to the mastermodel [cf. Thiele and Nuske, 2016]. With this flexible approach, improved submodels can be included once available.

Critical evaluation of submodels

Regionalization of climate As mentioned above, the implemented downscaling model published in Olchev et al. [2008] is based on the well-known 'ordinary kriging' method with height correction. However, when downscaling several interdependent variables, the interrelationships between variables should be taken into account. In the present study, the variables were adjusted to the mean daily temperature.

Phenological and allometric models To calculate the start and end dates of vegetation periods, the functions by Menzel [1997], Menzel and Fabian [1999], Wilpert [1990] are commonly applied in combination with the Brook90 model [Baumgarten et al., 2014, Schwärzel et al., 2009]. Furthermore, the site index of Albert and Schmidt [2010] uses this approach to summarize daily climate data for the vegetation period. It was therefore obvious to implement a corresponding approach, although the uncertainties were known, as described below. The work of Linkosalo et al. [2008] showed that simple thermal time models, as mentioned above, are very robust in predicting bud burst under current climate conditions. They commented that precautions were needed under changing climate conditions because the relative importance could be modified. Chuine et al. [2016] also postulated great uncertainty if using these models with climate change scenarios.

The LAI crucially affects the results of water budget models [Gigante et al., 2009, Wellpott et al., 2005]. Since the LAI is difficult to measure directly, high uncertainties are also introduced at this early stage [Nilson et al., 1999, Richardson et al., 2011]. The simple approach to modeling LAI dynamics from Law et al. [2001] used in this study considers only the interactions with stand characteristics (Dq, stem number). However, some studies have shown that there are feedbacks between the site water balance and LAI [Le Dantec et al., 2000, Schleppi et al., 2011], although Leuschner et al. [2006] failed to find a limiting effect of drought stress on LAI. It also has been shown that the site indices of forests correlate with the respective LAI [Bequet et al., 2012].

Specifications of effective rooting depth are very important for water budget modeling and drought stress mortality assessment. The architecture of root systems is mainly influenced by the parent material, the soil type, the bulk density, the chemical soil conditions, the depth of ground water, and the species and age of trees. Due to this complexity, the root depth

and the distribution in the soil profile are critical model parameters. The linking rule from Czajkowski et al. [2009] is based on numerous studies.

Nutrient index modeling The soil nutrient index classes are an input parameter for site index modeling. During preprocessing, the nutrient classes are pooled into three to four classes. Therefore, we decided to use a simple approach, which was very robust when applied in different federal states. However, nutrient regime modeling is more uncertain than modeling of the water regime for forests [Köhler et al., 2016].

Soil water and drought stress mortality modeling All water model predictions are linked to uncertainties, which are generated either by the model input data (climate, soil, and vegetation), the model structure itself or by the uncertainty of model parameters [Beven, 2012].

In a model comparison by Bouten and Jansson [1995], deviations from the average seepage flow rate of -6% to +12% resulted from the selection of different models. Although many models have been developed to address water budgets, the Brook90 model has demonstrated its potential in many studies [Baumgarten et al., 2014, Vilhar, 2016].

Despite the high potential mortality risk of forest trees, existing drought stress projections are based on models that lack functionally realistic mortality mechanisms [Adams et al., 2009]. Following Bréda et al. [1995], Czajkowski et al. [2009], who demonstrated that plant water status can be linked to soil matrix potential at the lower limit of the effective rooting depth (ERD), we implemented a drought mortality function in the water budget model discussed above. Accordingly, there are three main sources of uncertainty: the soil water model itself and its parameterization; the determination of the ERD, which is highly dependent on tree species structure and soil characteristics; and the parametrization of the mortality function, which is the main uncertainty. The results of Pedersen [1998] indicate that tree mortality is usually a decades-long process involving a combination of environmental stresses. However, the work of Bolte et al. [2016] showed that there is very low survival probability if the soil water availability falls below values of 20% and approaches zero. This is the case if the critical limits of soil water potential are exceeded [Czajkowski et al., 2009].

Site index and forest growth model The main purpose of the modeling system is to provide decision support for forest planning. Thus, the use of a statistical approach to project the site index under climate change is considered appropriate. For instance, Pretzsch [1996] argued in favor of statistical models as the best method to provide forest management information because these model formulations primarily project stand or tree development on a scale appropriate for practical decision support. However, many researchers view process-based models as best suited to analyze the effects of climate change on forest growth as they strive to understand the ecophysiological functionality of forests [e.g., Landsberg, 2003, van Oijen et al., 2008a].

The presented site index model incorporates main effects of climate parameters, nitrogen deposition and soil properties, in accordance with results from van Oijen et al. [2008b], who analyzed past growth trends applying four process-based models. However, interaction must be considered, e.g., between nitrogen deposition and soil nutrients [cf. Egli et al., 1998]. Although highly significant, including the interaction term of nitrogen and nutrients did not improve the model's coefficient of determination considerably.

Furthermore, variable selection must be critically evaluated because major predictors of forest growth might be missing, e.g., level of CO₂ [e.g., Handa et al., 2006, Körner et al., 2005]. We also observed a highly significant linear effect of the mean atmospheric CO₂ concentration on site index, and even an interaction term with soil nutrients was highly significant. Unfortunately, site index projections under elevated CO₂ concentrations yielded unrealistic high values. Thus, extrapolation of the linear trend is not permitted. The problem of projections outside the range of the parametrization data is generally discussed by Mendoza and Vanclay [2008]. A comprehensive evaluation of the site index model is given in Albert and Schmidt [2010].

In addition to evaluating the site index model itself, it is important to examine the impact of projected site index values as an input parameter in the forest growth model. The site index plays a major role as an independent variable in the tree height growth function. The sensitivity of the growth model to the site index is clearly visible when comparing the values in Table II.8 within an age class. While height growth is modeled in a site-sensitive manner, diameter growth is indirectly influenced because the predictor variable crown surface area is a function of crown length, which in turn is a function of tree height. However, the overall satisfying performance of the growth model has been proven in other simulation studies [cf. Albert et al., 2016, 2015].

Wind damage model The present study uses the 3D SCADIS model to evaluate wind load on trees in heterogeneous forest stands. Its implementation is substantiated and described in detail in Panferov and Sogachev [2008]. It could be argued that a three-dimensional approach with a high spatial and temporal resolution is rather time-consuming and considerably slows the system. However, realistic wind load estimations for heterogeneous landscapes can only be obtained using a 3D approach. The model can be switched to 1D if the stand and topographical conditions can be reasonably approximated as horizontally homogeneous. The implemented estimation methods for critical wind speeds are well known and validated [Panferov et al., 2009]. It is arguable whether empirical parameters obtained elsewhere, e.g., in Great Britain, are applicable to German forests. In the present study, we used the best available data. The modular structure of the system allows easy replacement of any parameter once better (i.e., stand specific) values are available. The novelty of the employed approach is the combination of empirical functions for critical levels with detailed information about wind load on trees, as well as interactions with other risk factors.

Bark beetle damage model The employed bark beetle damage model consists of two parts: a phenological model predicting number of beetle generation per year based on temperature sums and a damage model based on the output of the first part and predisposition caused by stand structure and soil moisture. Both model parts incorporate climatic conditions and are thus able to respond to a changing climate.

For the simulation of the phenology of bark beetle populations, we selected the PHENIPS model developed by Baier et al. [2007]. It is based on the well-known relationship between temperature and activity as well as reproduction of *Ips typographus* [Jönsson et al., 2007, Wermelinger and Seifert, 1999]. The model predicts the number of complete insect generations per year and is thus well-suited for the estimation of bark beetle outbreaks. A recent study by Berec et al. [2013] validating the PHENIPS model with measurement data confirmed this utility for a region outside of the area for which the model was developed.

The second part consists of a predisposition model and a damage probability model. We used the models developed by Seidl et al. [2007], which are based on the work of Netherer and Nopp-Mayr [2005]. The approach is based on the number of generations, stand characteristics and the soil moisture index as a drought stress indicator. Therefore, this approach was well-suited for our purpose. However, the approach could be improved by incorporating further predisposing factors, such as windthrow and snow breakage, that are currently not considered. Another potentially confounding variable is silvicultural activity, which pools factors such as active measures to reduce infestation risk and the intensity of thinning and harvesting operations to attain forest hygiene. Overbeck and Schmidt [2012] quantified the effect of silvicultural activity based on the random effects on the forest sub-district level in their mixed model approach on infestation risk. Furthermore, conditions in neighboring stands are not included in our model. Moreover, a main challenge remaining in modeling bark beetle damage to managed forests is the availability and quality of measurement data for model development and validation. Recorded data is often not available to the public due to business secrets.

Economic model The mean annual contribution margin of timber production under risk within a given period is determined using a survival function based on an approach presented in detail by Staupendahl and Möhring [2011]. The survival function gives the probability that a given stand reaches or even exceeds a specific age. Because the prediction of the time of occurrence of calamities, which are assumed to completely destroy the stand, is associated with high uncertainties, the survival function is a simple linear function starting with 1 at the beginning of the respective period and ending with the probability that the indicator stand survives the period. Thus, the conditional drop-out probability is constant within the period.

This approach enables the determination of the discrete frequency distribution of the stand's survival time and thus of the distribution of the periodic annual contribution margin and its expected value. These properties obviate Monte Carlo simulations. The Monte Carlo approach, which has been used by many other authors [e.g., Brumelle et al., 1990, Dieter, 2001, Kuboyama and Oka, 2001], requires more complex software, large numbers of iterations, long extrapolation periods, and, consequently, more time to answer the user's request.

However, the level of abstraction in the economic model and, consequently, the deviation from reality cannot be ignored. Calamities regularly create small gaps that will reduce the density of stands. The alterations in the growth of the remaining stand due to the reduced stand density are not accounted for. Furthermore, interdependencies between risk and stand treatment are not considered, although the timing, type, and intensity of thinnings drastically influence the risk disposition of stands [e.g., Dobbertin, 2002, König, 1995]. Finally, other sources of risk, e.g., the risk of timber price fluctuation, were ignored, thus permitting, however, the identification and analysis of the pure effects of natural hazards.

Assessment of climate change impact

Ecological impact The simulation of the growth potential (site index) showed that, in total, a remarkable improvement of tree growth can be expected for spruce in the study area under climate scenarios B1 and A1B, mainly due to the increasing temperature sums in the vegetation period. The elevation-dependent growth differences diminish in the projection

periods because stands on higher elevations benefit disproportionately from the temperature increase, which is especially pronounced under climate scenario A1B. The spatial pattern of the site index in Figure II.14 indicates the effect of the temperature rise and extended vegetation periods, which overcompensates the effect of the decreasing water balance, resulting in the increase in the growth potential of the stands over time. These results are difficult to compare to those of other regional studies because the response of growth appears to differ greatly depending on species and region [e.g., Albert et al., 2015, Lasch-Born et al., 2015]. Drought seems to be a particularly limiting factor for other regions. However, Lasch-Born et al. [2015] indicated that an increase in the site index is plausible in the study region, in good accordance with observations by Pretzsch et al. [2014].

Thus far, one could assume better growing conditions in the study area in the future under the applied climate projections. However, our damage risk assessment dampened expectations. We found a strong increase in the probability of drought stress-induced tree mortality in the period 2071–2100 for scenario B1 and in period 2041–2071 for scenario A1B. This increase in risk is mainly driven by several single extreme events. However, projecting the exact time and strength of extreme events is impossible; therefore, these findings are interpreted as probabilities. Furthermore, trees dying due to water shortage is currently a very rare phenomenon in the study area and in Central Europe in general [Allen et al., 2010]. Therefore, models predicting the risk of tree mortality caused by drought stress contain large uncertainties. Studies compiled by Adams et al. [2009] suggest, however, that tree mortality risk will increase due to the projected future warming and drought, even in regions that are not considered water limited.

However, the main and more important effect of dryer soil conditions is the higher risk of bark beetle outbreaks. The detection of trends of those extreme events is one of the main advantages of the direct model approach. For the bark beetle infestation risk, we observed a more general trend of increase over the years, reflecting the temperature increase and changes in the seasonal distribution of precipitation. We observed a higher vulnerability, especially in the lower northern part of the study area, which has higher temperatures than the hilly southern parts. The general pattern of infestation risk increasing under climate change is in good accordance with studies by Overbeck and Schmidt [2012] of the Harz region in Central Germany and Seidl et al. [2007] of Austria.

The risk of wind damage also increases over time. Furthermore, the risk distribution between the age classes changes. The first two periods are characterized by higher risks in younger tree stands, possibly due to the lower wind level threshold for tree damage, which could be eventually attributed to smaller rooting depth and higher levels of soil moisture, which weaken the anchorage of younger trees more. Thus, younger trees might be damaged even by weaker (slower) winds. The results are in agreement with those of a study by Panferov et al. [2009] of Norway spruce and Scots pine. In the projection periods, the values of the critical wind speed (wind that damages the tree) become similar for the young and old age classes. However, older trees, which are taller, experience higher wind speeds (wind speed increases with height), and this, under the same threshold values, might be responsible for the higher damage risk probability for older compared with younger trees. The increased probability of wind damage for all age classes in the projected periods is a direct response to the increased probability of stormy days as well as the increased temperature projected by the climate scenarios. This effect might be strengthened by changes in stand structures due to improved and differentiated growth and, consequently, intensified harvesting driven by reaching the target diameter earlier. In turn, this results in larger inter-

tree distances, which is an important input for determining critical wind speeds [Panferov et al., 2009]. This change increases the wind damage risk. The general trend of increased wind damage risk is in good accordance with studies of other regions by Leckebusch et al. [2007], Blennow et al. [2010], Albert et al. [2015]. Furthermore, our findings correspond with the results for projected wind damage predisposition in the study area by Klaus et al. [2011]. The near tripling of the drop-out probability in both climate scenarios seems to be plausible because Schelhaas et al. [2010] presented a tripling of exposure under a climate change projection for the year 2100 for Denmark as well. Moreover, Schelhaas et al. [2003] identified wind as the most important disturbance agent in the past. Our simulation results show that wind could also be the strongest disturbance agent in the future.

Economic impact Integrating the different risks into a joint economic assessment revealed a strong increase in risk costs, reflecting increases in the three modeled individual risks. Whereas the strongest increase was observed in the last period in scenario B1, driven by a sharp increase in the drop-out probabilities of wind and drought, risk costs already increase strongly in the second projection period for scenario A1B. These results substantiate a profound change in production conditions.

Although a strong increase in risk costs was projected, we found an increase in the mean annual contribution margin under consideration of risk costs to the end of the century for the first two age classes and a slight decrease for the age class 90–120 years. The higher productivity (site index) compensates for the higher risks under climate change at several sites. Therefore, earlier harvesting, even due to hazards, produces an increased economic return. However, macroeconomic effects in case of large-scale hazards are not covered by the economic submodel. Market prices may change after hazards, and timber prices and costs may no longer be constant. Moreover, since stand survival is calculated solely by combining the conditional survival probabilities of drought, wind, and biotic risks, the assessment neglects some feedback effects. Without any potentially intensifying feedback effects, e.g., bark beetle attack after windthrow, the simulated risks are a conservative estimate. Damage is interpreted as area loss and is not realized in the model stands. Reducing the number of trees due to risks would result in lower tree density and more deadwood and, in turn, could further increase the vulnerability of the stands to biotic and abiotic risks [cf. Hanewinkel et al., 2008]. For example, opening up of the standby bark beetle damage can increase the vulnerability to wind damage. In turn, foresters can actively reduce these risks by appropriate management and planning.

Consequences for forest management From a forest management perspective, the simulation results indicate that under the applied climate scenarios, Norway spruces should not be established in areas with low available soil water capacities. To reduce the wind damage risk, the stability of the stands should be increased through appropriate measures. For instance, an early increase in the height-diameter relation by reducing the number of stems per hectare and avoiding intensive thinning in later phases can increase stability. Furthermore, it is advisable to shorten the rotation period since the risk costs increase with the stand age and might counterbalance the positive effects of growth improvements for old stands. Because the site index simulation projected accelerated growth in the future, target diameters will likely be reached earlier (cf. Table II.9). Last but not least, careful pest

control and forest management have a very high influence on the damage risk due to bark beetle infestation.

II.3.6. Conclusion

The complex dynamic simulation model system is a promising approach to assess the impact of climate change to Norway spruce and forests in general based on high-resolution climate data. The 'indicator stand' concept permits a comparison of the effects of climate change at different stand ages. We have shown that the application of the modeling system to the 'Arnsberg Wald' produces plausible results and enables forest managers to plan site-specific adaptation and risk avoidance strategies. This study employs only one realization of two climate scenarios and is thus limited in its prediction of damage impacts. If more climate scenarios, realizations, and models are available to the user, the model system can easily be used to process comprehensive ensembles.

We believe that dynamic modeling approaches are most appropriate to assess climate change impacts if these changes are characterized by extreme events, shifts in temporal distributions and non-monotonous trends.

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CHAPTER III

Bio-Energy Allocation and Scenario Tool

SECTION III.1

A Decision Support System to Link Stakeholder Perception with Regional Renewable Energy Goals for Woody Biomass

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Authorship

- Gerald Busch supported the conception of the BEAST and made language edits on the manuscript.

III.1.1. Abstract

In light of the ambitious climate protection goals adopted by the European Union (EU) and member states such as Germany and especially since the nuclear disaster in Fukushima, the use of renewable energies has become a widely discussed topic. Several cities and municipalities in Germany have begun to develop climate management plans at the local political level. One aspect of such plans is the use of regional woody biomass. However, detailed analyses of the potential reserves, and of the economic and ecological consequences of using these, are often lacking due to the absence of data and the necessary tools. In this paper, the authors describe how several results of the BEST project were integrated in a decision support system (DSS), making it possible to create and evaluate different scenarios of the use of woody biomass for energy production. Using this tool, political goals can be assessed in the context of the available biomass potentials and the corresponding economic and ecological criteria.

III.1.2. Introduction

Electrical and thermal energies are the basis of our modern, technically minded civilisation. Sources of fossil fuels are running short [Hirsch et al., 2005] and environmental impacts, especially from climate change, are becoming an increasing problem [Stocker et al., 2013]. Against this background, the European Union (EU) has committed to increasing the proportion of renewable energy from 12.7% at present to 20% by 2020 [European Parliament, 2009]. The German government has adopted more ambitious targets while also undertaking to phase out nuclear power. The German Renewable Energy Act requires an increase of the contribution of renewable energy to overall electricity consumption of at least 20% by the year 2020, 50% by 2030, 65% by 2040 and 80% by 2050 [EEG, 2009]. The interest in renewable energies has grown noticeably in recent years, therefore, and can be expected to increase further in the future.

In the context of the German National Climate Initiative, the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety is funding cities and municipalities in their attempts to develop strategies for regional climate protection [Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB), 2013]. Achieving regional energy autonomy by the year 2050 as the ultimate goal, these strategies must target a 50% reduction in the energy demand and full provision of the remaining energy needs using renewable energy [Bundesministerium für Umwelt, 2012].

Biomass is one of the various resources necessary for the provision of renewable energy. The climate management plan for the Göttingen area accounts for the use of 10% (moderate scenario) and 20% (ambitious scenario) of the arable land in the region for bioenergy production: 4564 and 9127 ha, respectively [LK Göttingen, 2013]. Firewood, small dimension wood, forest residues and woody biomass from outside forests, for example, from shade trees and hedges, are also taken into account.

Such climate management plans are created on the basis of stakeholder forums, expert panels and scenario calculations. However, the detailed analyses of biomass potentials and the consequences of and for land use are often lacking. To fill this gap, a decision support tool was developed enabling users to create and evaluate scenarios of woody biomass utilisation. The tool was developed in the context of the BEST project, for the study area Göttingen. The conceptual framework and implementation, however, were designed to be

adaptable to other regions. In the following, the concept behind the data- and model-driven, multipurpose decision support system (DSS) is presented.

III.1.3. Decision Support Tool Concept

The description of the DSS concept in this chapter follows the overview, design concepts and details (ODD) protocol [Grimm et al., 2006, 2010], which was originally designed for agent-based models but also fits well (with certain adaptations) to other model types. It provides a model description with an increasing level of detail, starting with very general information from a meta-perspective and progressing to a very detailed description at the end of the documentation. The focus here will remain on the general description.

Overview

Purpose The DSS was primarily designed to create and evaluate scenarios of woody biomass use. The target audience are stakeholders in regional political climate protection planning processes. The objective is to visualise political targets, check their feasibility and reveal their consequences in economic and ecological dimensions. It calculates woody biomass potentials from various sources. In the case of short rotation coppice (SRC), it identifies preferred field locations on the basis of multiple criteria. This system is meant neither for operational planning by farmers nor for use in regional planning procedures.

Entities, State Variables and Scales The DSS recognises three sources of woody biomass or entities: wood from forests, wood from outside forests such as shade trees and hedges and wood from SRC on arable land. Field crops are also incorporated in the DSS for comparative purposes.

The state variables are primarily the demand for energy from woody biomass within a simulation period and the reserves of woody biomass from the aforementioned sources. The DSS stores economic values in terms of an annuity of the revenues and costs for all biomass sources. For each arable field geometry [see Busch and Thiele, 2015], it calculates the difference between the hypothetical annuity provided by SRC and a typical field crop rotation. Moreover, the DSS indicates whether specific restrictions apply or objectives are met, and whether a field is classed as a potential SRC location, and in which quality class.

The values of scaled criteria (explained in next section), and their sum, serve as a basis for the process of selection of potential SRC sites on arable land. It is possible to classify the criteria sum and so to rank the suitability of the selected SRC preference sites.

The system's output is presented for two 20-year periods: 2011–2030 and 2031–2050. Internally, the length of the calculation steps differs. The economic calculation is based on a 1-year step, whereas harvesting in forests and of wood from outside forests takes place at 10-year intervals. Field crops are harvested annually and SRC at 5-year intervals with an operational time of 20 years.

The system's spatial extent, as presented here, is the Göttingen region (Landkreis Göttingen), located in the middle of Germany and covering an area of approximately 1117 km². The system can, however, be applied to any desired area, once the appropriate input data are available.

In the system, wood from forests and wood from non-forest sources are aggregated for the whole research area, although the corresponding input data are generated spatially

explicit. The modelling of SRC is spatially explicit. The field geometries of arable plots in the Göttingen region [see Busch and Thiele, 2015] are used for the simulations of field crops and SRC. The system itself is virtually independent of spatial scale; the input data define the spatial resolution of the calculation.

Process Overview and Scheduling The whole process, depicted in Figure III.1, runs twice, that is, separately for both 20-year time intervals. The parameters and input values are stored in separate files compressed into a single file with a .best extension. Where necessary, the first 20-year interval parameter values are prolonged (e.g., basic prices and costs, yields) before the second run starts.

The calculations for the three biomass sources, as shown in the grey box in the middle of Figure III.1, are independent of each other (Figure III.2). Thus, scheduling is relevant only within the three calculations described in separate paragraphs below.

- *Forest Wood.* Forest wood is divided into four sub-sources: stem wood, industrial wood, firewood as a proportion of the industrial wood used for energy generation and wood residues converted to wood chips. In a first step, the biomass potential from thinning is calculated in 10-year intervals for each of these sub-sources according to the particular scenario settings. Next, this biomass potential is assessed economically. Finally, the results are aggregated for a 20-year interval and saved.
- *Wood Outside Forests.* The processes and scheduling for the source wood from outside forests are as for the forest wood. Stocks, where available, and their cumulative growth are summed to a total biomass potential for a 10-year period. This potential is assessed economically, aggregated to a 20-year output period and stored for later use.
- *SRC.* The processing of SRC includes the processing of field crops (Figure III.3), refers to the specific geometries of arable fields and is, therefore, spatially explicit. In a first step, both the yields produced by SRC and field crops (oilseed rape, wheat, barley, maize, sugar beet) are calculated annually for a 20-year period. Based on this yield computation, annuities are derived for the various crops applying a dynamic investment calculation [see Kröber et al., 2015]. In a next step, the crop rotation-specific annuity is calculated and subtracted from the annuity provided by SRC. Upon completion of the economic calculations, a multi-step procedure for the selection and classification of potential SRC sites begins. A corresponding process is not required for the other wood sources as no land use change is implied.
 1. *Restrictions.* First, area restrictions are applied and a flag indicating whether a particular arable field fulfils the selected restrictions is set and saved. Fourteen area restrictions are implemented in the current version, including restrictions due to nature conservation or planning goals. Also included is a maximum possible proportion of SRC on arable land per fixed spatial unit. For this study, spatial units were defined at administrative (municipality) and ecological level ([sub-] water catchment areas). These restrictions on SRC are applied within the area selection routine.
 2. *Objectives.* Next, a set of nine area objectives can be addressed. The user is allowed great flexibility in defining how each should be met. For each criterion (e.g., erosion potential, landscape diversity, soil quality index), the user is able

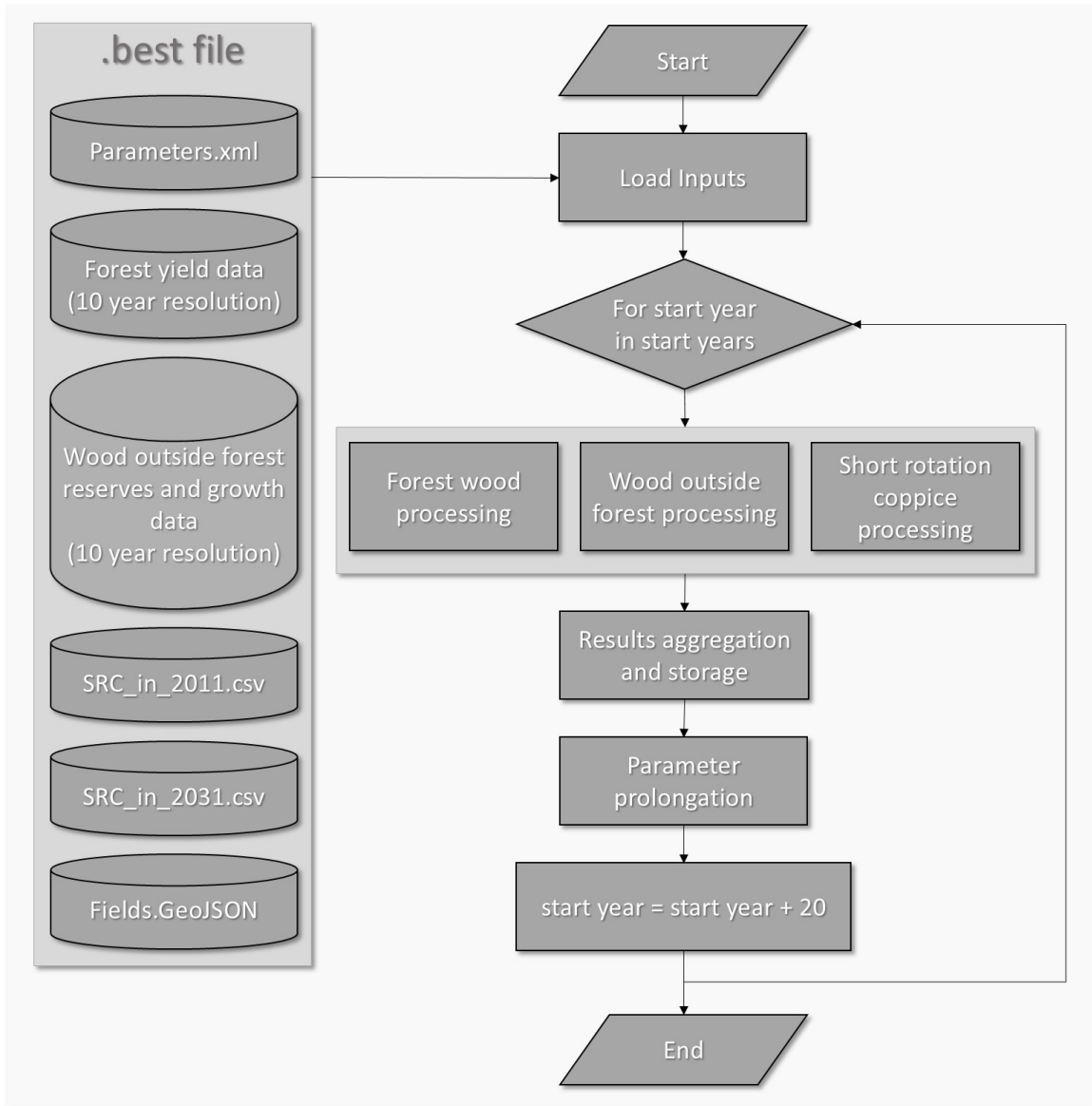


Figure III.1.: Process overview of the DSS with parameter and input files on the left and processes on the right. One loop over the possible wood sources calculates values for a 20-year period. Details on the processing of the wood potentials are provided in the text and in Figure III.2.

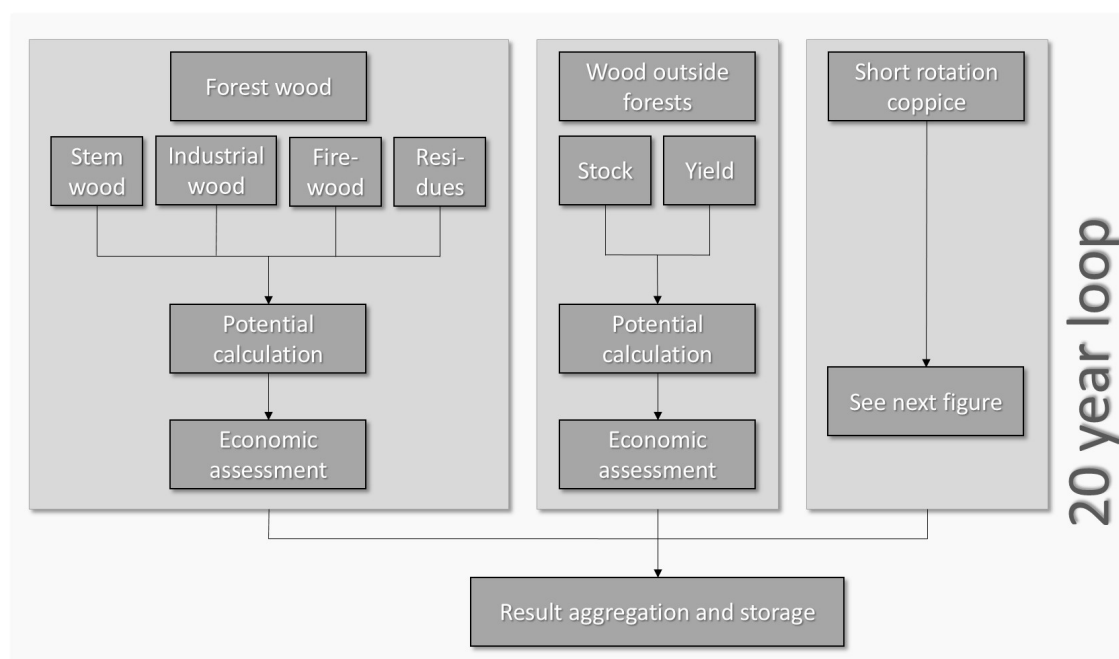


Figure III.2.: Overview of the process flow (without data flow) for a 20-year interval, excluding details for short rotation coppice (presented in Figure III.3).

to define the minimum and maximum boundaries to qualify the arable field for selection. Here, again, a flag marking whether a particular field fulfils the objectives or not is set and stored.

3. *Criteria Scaling.* In a third sub-process, the user can further refine the application of criteria by shaping a criterion-specific course when defining additional values within the threshold range set in the previous step. Criteria values and corresponding scaling values ranging between 0 and 100 must be put into a matrix. Linear interpolation between these value pairs results in a criterionspecific course. This procedure can be adopted for all ecological criteria and the user-defined economic targets for SRC and allows for the application of a multi-criteria analysis in subsequent procedures within the DSS. Five value pairs can be used to define the scaling of each criterion. The scaled criteria values are stored for each field.
4. *Criteria Weighting.* A user-defined criteria weighting (Figure III.4) is multiplied by the scaled criteria values and then summed to a criteria sum, which is again scaled from 0 to 100, depending on the theoretical maximum sum value based on the selected weightings. This scaled criteria sum is also stored along with the field attributes.
5. *Area Selection.* Once all of the values for the area selection and prioritisation have been collected, the selection process starts by subsetting those fields that fulfil the restrictions and objectives simultaneously. This subset is then sorted by decreasing criteria sums. Before the subset of fields is processed for SRC selection, the area sum of all fields belonging to an administrative unit is calculated. This is

done to determine the maximum area that may be selected as SRC within an administrative unit, transformed from the user defined maximum percentage per unit. The same procedure is carried out for the ecological units. The subset of arable fields fulfilling the restrictions and objectives, sorted by decreasing criteria sum, is then processed. A field is flagged, and the corresponding field area is subtracted from the maximum allowed area within the corresponding administrative and ecological unit. If the size of the selected field is smaller than or equal to the permissible SRC area of the administrative and ecological unit, it is kept; otherwise, it is skipped. In an optional advanced mode, it is possible to request a minimum distance between two SRC fields. If this algorithm is applied, all field geometries selected so far are stored in a list. The current field geometry is buffered with the minimum distance and checked for intersection with all other fields in the list of potential SRC fields. Only where there is no spatial intersection is this field also defined as a potential SRC field; a flag is set, and its geometry is added to the list of potential SRC fields. At the end of the SRC selection process, selected SRC fields are categorised into five classes describing how well they fit the criteria based on the scaling and weighting using the scaled criteria sum. Finally, some aggregations are calculated; the results and a set of intermediate results are stored.

Design Concepts

Basic Principles. The system is data- and model-driven. As many input data as possible are preprocessed and transferred to a common import file structure. This procedure guarantees high flexibility as the system itself is independent of yield and growth models and modelling approaches. It serves as a shell for scenario and decision analysis. Apart from modelling flexibility, preprocessed data allow for faster processing and generation of results: a second major objective when designing the system. The emphasis was on providing users with a prompt response upon making changes to the input parameters. By playing with the values and seeing the consequences, users discover how parameters and changes to parameter settings affect the results. The addition of imposed minimum distances between SRC fields slows down the simulation considerably. This is tolerable, however, as this geoprocessing function is for advanced use and only applied in certain circumstances.

The system is 'climate change ready'. Input files contain yield values for 10-year periods (5 years for SRC) and can, therefore, reflect yield changes under a changing climate.

As field geometries are also imported into the system from files, they too are not fixed. It is a simple task to change the research area, zoom into specific sub-areas and alter the spatial resolution.

Emergence. The spatial pattern of the potential SRC fields selected derives from the user-defined restrictions, objectives, criteria scaling and criteria weighting.

Objectives. The system optimises the identification of potential SRC fields with respect to criteria scaling and weighting.

Stochasticity. The system includes no random effects.

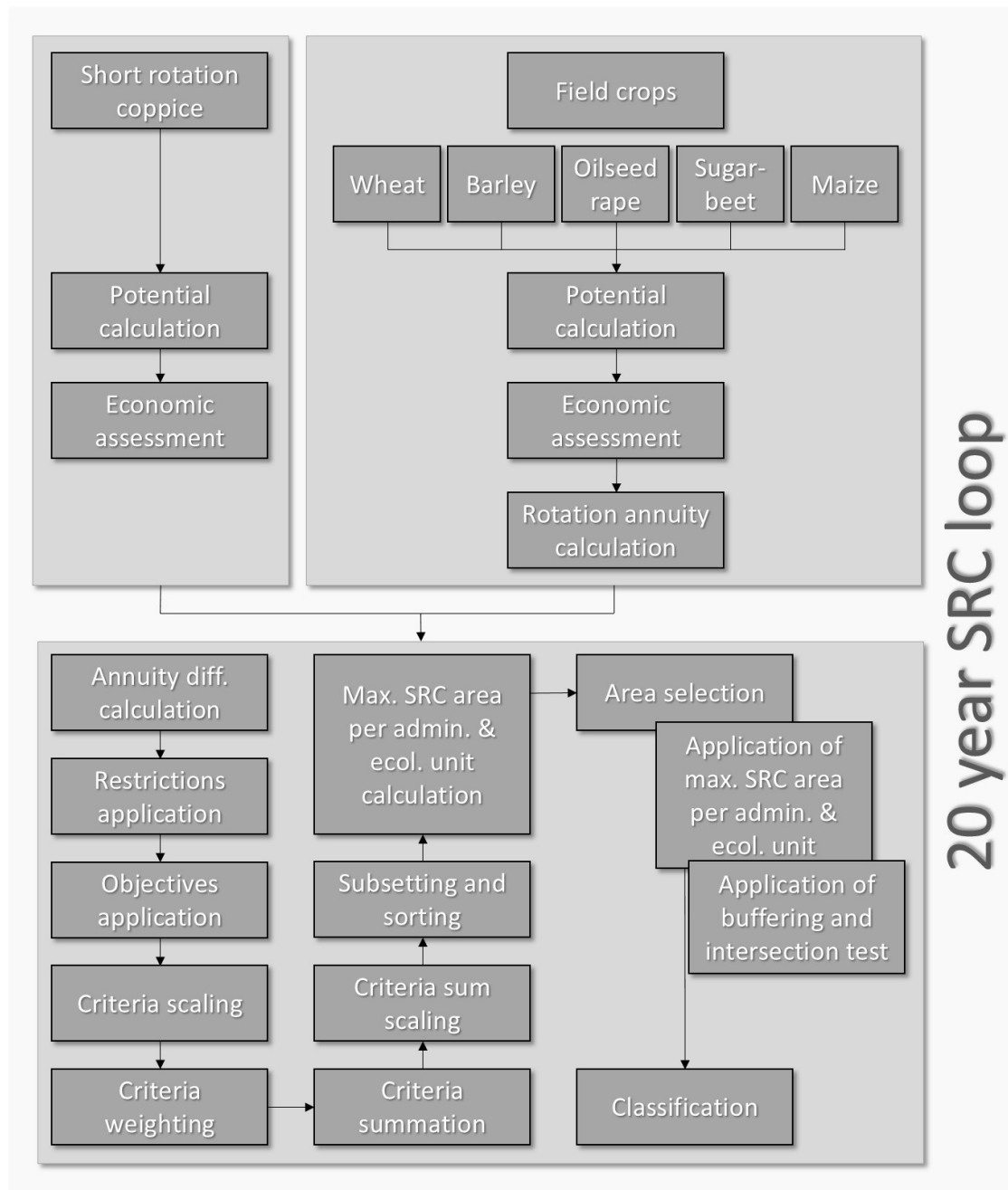


Figure III.3.: Process flow overview (without data flow) for a 20-year short rotation coppice sub-process interval.

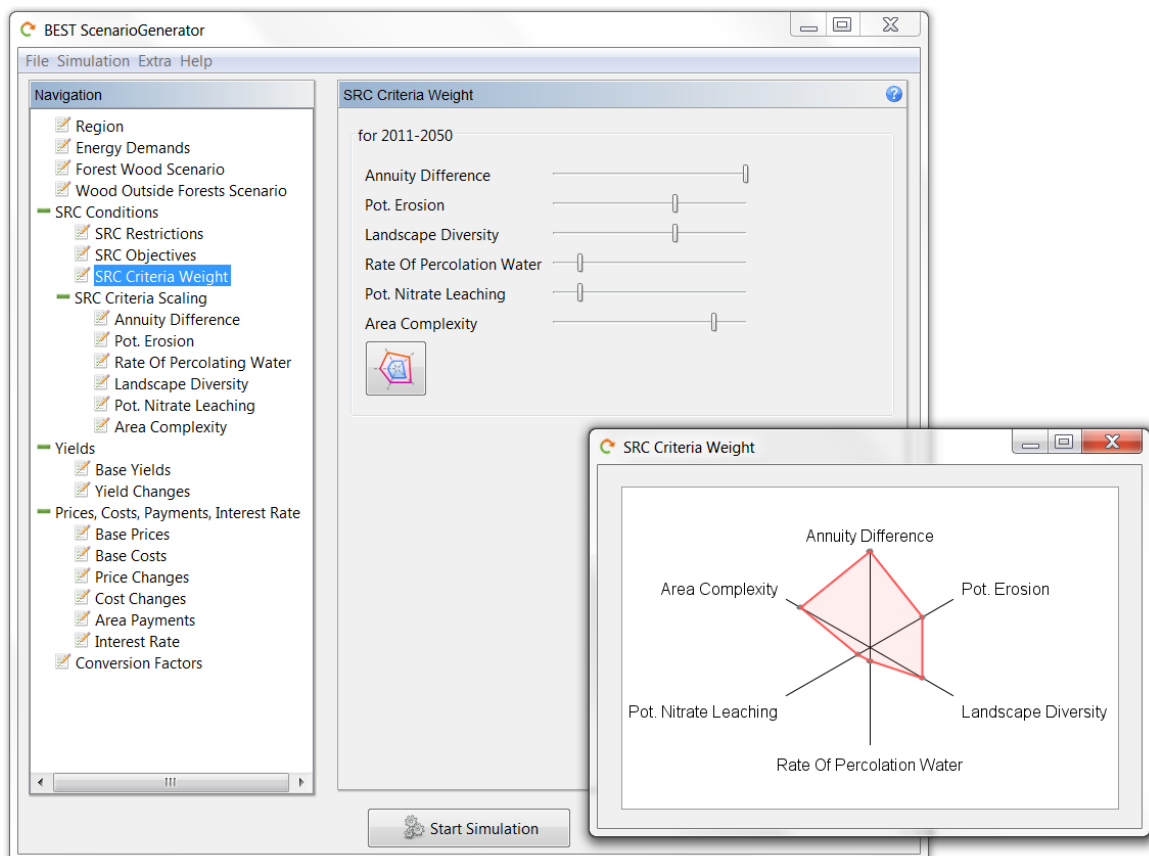


Figure III.4.: The ScenarioGenerator window showing the SRC criteria weighting form and an open window depicting the corresponding spider graph.

Observation. Biomass demand and supply figures, primary energy equivalents and annuities are stored during the simulation for all wood sources. The annuities for all field crops and crop rotations are also saved. The same applies to scaled criteria values, the scaled criteria sum and flags reflecting (i) restrictions and objectives met, (ii) potential SRC fields selected and (iii) the SRC classification stored for further analysis.

Details

Initialisation At the beginning of the simulation, the biomass and energy state variables are sourced from the input files. The input files for the forest part of the DSS should ideally be generated from stand growth simulations based on inventory data. Therefore, the underlying forest stands are represented in their current state or, if the inventory data are older, their state at time of inventory extrapolated to the present using a growth simulator. A similar procedure is carried out for the wood from outside forests component, with stock and growth values assigned and summed up rather than referring to a ready-to-use harvesting value. In the case of the SRC part of the DSS, each 20-year simulation step starts from scratch. The operation time of an SRC is assumed to be 20 years, meaning that before and after a 20-year simulation step, all planning options are available.

Input Data The input data are compressed into a file with the extension .best, which contains several sub-files (Figure III.1, left). Parameters of the simulation such as interest rate, regression parameter values of cost functions, rates of change associated with prices and costs, restrictions and scaling support points are stored in the parameters.xml file. This file is loaded into the memory, initialises the graphic user interface (GUI) for the scenario inputs and changes according to the user input. A complete set of parameters for each 20-year simulation period is contained in the parameter file. For the second period, values that change over time such as prices and yield are prolonged using the adopted rates of change.

The harvested forest biomass (10-year intervals) is provided in the forest_in.csv file. It contains the harvested biomass for each forest compartment reflecting two scenarios: with and without Forest Stewardship Council certification. Biomass stock and yield values for wood from outside forests (10-year periods) are imported from the landscape_in.csv file. The necessary input data for each arable field are derived from the src_in_2011.csv and the src_in_2031.csv files for the periods 2011-2030 and 2031-2050, respectively. Each row in the dataset represents one field with columns for yield values for the different field crops (at 10-year intervals), yield values for SRC (at 5-year intervals representing the SRC rotation length), the different original ecological criteria values, information about the site such as size, slope, the corresponding administrative and ecological unit number and, where applicable, protection status. Field geometries corresponding to the rows of the SRC-specific .csv-files are included in the fields.GeoJSON file, joinable by a bestid column, for geoprocessing functions and the MapViewer application.

III.1.4. Implementation

The DSS runs as a desktop application in the Java programming language [Oracle, 2014]. The GUI were programmed using Swing components integrated into Java and using the JGoodies libraries [Lentzsch, 2014]. The JFreeChart library [Gilbert, 2013] was employed for the various charts. The parameter file is bound to Java classes using the EclipseLink MOXy

library [Eclipse, 2014], whereas the .csv file is parsed with the help of the opencsv library [Smith et al., 2011]. The geoprocessing functions and the MapViewer use the GeoTools library [GeoTools, 2014], the multi-language GUI support relies on the Apache Commons Lang library [Apache Software Foundation, 2014a], and the Log4j library [Apache Software Foundation, 2014b] is used to log messages. Maven [Apache Software Foundation, 2014c] is employed for an automatic build process.

The system is split into three main GUIs: the ScenarioGenerator (Figure III.4), the ResultsExplorer and the MapViewer. Additional windows are created for graphs. With the ScenarioGenerator, the user can define the scenario by changing the values of state variables and parameters. Several graphs support the user in finding meaningful values. From here, the simulation process (Figure III.1) can be started. The results of a scenario simulation can be stored in a file or loaded directly from memory into the ResultsExplorer. The results of several analyses of various aspects can be processed and presented in the form of tables and graphs. The MapViewer, a small geographic information system application (GIS), can be opened from the ResultsExplorer. Various predefined layers depicting different results for the SRC and field crop options can be added to the map for viewing and spatial analysis. The results and spatial data can also be exported for further analysis using external software.

III.1.5. Discussion and Conclusions

The DSS developed within the BEST project allows users to evaluate political goals and analyse woody biomass potentials with respect to possible trade-offs and synergies between economic and ecological criteria. Questions concerning the available quantities of woody biomass are expected to become more frequent in the future as climate protection plans become standard in cities and municipalities. The importance of the role biomass will play in these concepts is underlined by the fact that in 2012 biomass accounted for more than 30% of the supply of renewable energy in Germany [Netztransparenz, 2013].

To the best of the author's knowledge, this is the first system specialising in detailed scenario analyses with respect to woody biomass potentials, and the corresponding consequences, operating at the regional level and with a focus on the political perspective. There are a growing number of DSS and potential analyses in the context of bioenergy, but these focus on different aspects or levels of detail. Past research can be separated into different categories:

- DSS focusing on larger or different contexts but with less detail, for example, whole supply chains [Buchholz et al., 2007, Trømborg et al., 2011, Alam et al., 2012, Kühnmaier and Stampfer, 2012]
- DSS with a higher level of detail but lower general applicability or focusing on economic decisions while excluding political decisions, for instance, the siting of mills or power plants [Voivontas et al., 2001, Jones et al., 2008]
- Studies incorporating potential analysis, possibly at the same level of detail, but with absent user-friendly DSS software that would enable users to learn about cause-effect relationships and allow them to create their own scenarios [Rounsevell et al., 2005, Wu et al., 2012]

There were strong similarities between the approach presented here and that adopted by Sacchelli et al. [2013]. The latter focused on wood from forests only, however. The system presented here fills a gap between these existing approaches.

Being spatially explicit, it facilitates the bridging of the gap between sustainable land management and regional climate protection goals. The DSS can be used to further understanding of options and cause–effect relationships when discussing climate protection concepts and their realisation. It may also be used to help foster dialogue between different groups of regional actors and to facilitate common agreements.

Although the idea behind the system is rather simple, it is extremely complex in practice as the assessment of land use is an exacting task. As with all tools, finding a balance between usability and complexity is crucial. Ultimately, usability is reflected by acceptance by the target group, a factor often not considered sufficiently [Wright et al., 2011]. As part of the development process, acceptance was checked by presenting and discussing the system with regional actors representing various interest groups. The reactions inspire confidence that the DSS will be used upon release. The participants agreed that the degree of complexity represented in the current version is sufficient and that flexibility in its adaptation is of greater importance. Certain additional functions have already been added to address specific requests of the target audience. It is possible to replace criteria sets without rebuilding the system architecture. However, key factors in the long-term success of any such simulation system are continuous adaptation, improvement and support, factors often hampered by a lack of funding.

III.1.6. References

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SECTION III.2

Participative Dendromass Bioenergy Modeling in Regional Dialogs with the Open-Source BEAST System

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III.2.1. Abstract

Regional participative decision-making processes are becoming increasingly important in the context of climate change mitigation goals and renewable energy production. Dendromass bioenergy plays an important role in climate protection planning at the local and regional levels.

The 'Bio-Energy Allocation and Scenario Tool' (BEAST) is a decision support system designed to assist in stakeholder dialogues, with the goal of developing scenarios of regional wood production through scenario quantification and visualization. While it incorporates wood from forests and outside of forests as bioenergy sources, its main application area is the spatial selection of preference sites for Short Rotation Coppices on arable land, based on the integration of ecological and economic assessments in a multi-criteria analysis with preference selection using Analytic Hierarchy Process (AHP).

This paper provides a comprehensive overview of the purposes of the system, its simulation and software design, and also announces the system's availability as open-source software.

III.2.2. Introduction

Climate change, increasing energy demand and shortage of fossil fuels are major global challenges affecting energy usage today and especially in the future [IEA, 2016]. Thus, the European Union (EU) has been promoting the use of renewable energies, with biomass for energetic use as one important component by mobilization of existing reserves and the development of new systems [European Parliament, 2009].

For example, it is expected that up to 26 % of Germany's energy demand in year 2050 can be covered by domestic biomass [FNR, 2017]. In Germany, a financial support for the production of renewable energies including biomass was established with the Act on the Development of Renewable Energy Sources in 2000 and its successors [German Parliament, 2000]. This stimulated the bioenergy production from 586 GWh in 2000 to 41'016 GWh in 2018 [Federal Ministry for Economic Affairs and Energy, 2017]. The largest shares of bioenergy in Germany are produced with maize and oilseed rape [Schmidt-Walter and Lamersdorf, 2012]. For example, the area for energy maize production increased from year 2007 to 2017 by approx. 4.5 times to 1 Million ha [FNR, 2017, 2018]. However, the production of energy maize needs a relatively high energy input compared to perennial energy crops [Boehmel et al., 2008] and there are indications that the large maize monocultures result in a loss of biologic diversity [Eggers et al., 2009, Sauerbrei et al., 2014]. Furthermore, maize and rapeseed production implies high risk of erosion, nutrient inputs in ground and surface water as well as pesticide pollution of soils and water [EEA, 2006]. Due to these implications, not only annual energy crops should play a significant role in the projected energy mix but also the utilization of dendromass [BirdLife International and European Environmental Bureau and Transport & Environment, 2014, Schellnhuber et al., 2009].

In addition to the usage of waste wood, which is already almost exhausted [FNR, 2018], there are three possible sources for bioenergy production using wood: forests, wood from outside forests (trees and hedges of open landscapes and roadsides), and plantations of short rotation forests/coppices on arable land. In Germany and perhaps in most other Central European countries, there are source-specific restrictions on the usage of such sources as bioenergy, as summarized in the following.

The usage of stem wood from forests as bioenergy competes directly with the material use of stem wood and is therefore ecologically and economically problematic. Bioenergetic utilization of stem wood reduces long-term carbon sequestration and is thus inadequate for green-house gas mitigation [Schulze et al., 2012]. Additionally, the usage of residues from forests is under discussion due to questions of nutrient removal and accelerated release of carbon [Vanhala et al., 2013].

Woody biomass from open landscapes, i.e., hedges and trees outside forests or woodland, could be an additional source of woody bioenergy but is often not taken into consideration. However, from this source, Seidel et al. [2015] expects an annual supply of 233 TJ, based on a district in Germany with an area of approx. 1.100 km^2 . A study by Drigo and Veselič [2006] for Slovenia estimates a usable annual non-forest woody biomass volume of approx. 300.000 m^3 . As trees and hedges in open landscapes must be cut often as part of landscape tending measures, costs could be compensated by energetic usage [Schönbach and Bitter, 2015]. However, accessibility restrictions on machineries, missing utilization chains, and the reluctance of landowners and stakeholders all limit the usage of this biomass source [Seidel et al., 2015].

Another option is the production of woody bioenergy on arable land with Short Rotation Coppice (SRC). Planting SRC on arable land has many ecological advantages compared to the annual energy crop production. SRC is a low-intensity perennial agricultural system that can support various ecosystem functions and services, such as protection from nitrate leaching [Bredemeier et al., 2015, Schmidt-Walter and Lamersdorf, 2012], fragmentation of homogeneous arable landscapes [Baum et al., 2012], increased biodiversity [Rowe et al., 2011, Sage et al., 2006], reduction of soil erosion, lower fertilizer requirement, and sequestration of soil organic carbon [Blanco-Canqui, 2010, Don et al., 2012]. Due to its positive effects on soil and water quality SRC can also be cultivated on former cropland which has been abandoned due to soil and water issues [Schmidt-Walter and Lamersdorf, 2012] and is optimal for the transition of marginal land [Holland et al., 2015]. However, there is a strong reluctance of landowners to establish SRC due to the initial investment, the long-term (20 yrs.) and binding nature of the decision, missing supply chains, as well as a lack of information and experience although SRC is an interesting option for areas of lower site quality [Drittler and Theuvsen, 2018, Verwijst et al., 2013, Faasch and Patenaude, 2012, Schweier and Becker, 2012, Dimitriou et al., 2011]. Furthermore, the economically competitive of SRC to annual crops was already proven, when proper sites are selected [Kröber et al., 2015].

Achieving ambitious political goals for the increase in woody biomass supply for energetic usage requires involving various stakeholders in discussion and participation processes in order to implement regional strategies. Several constraints, including aspects of ecological sustainability and economic advantage, are restricting the increased usage of existing biomass sources. Furthermore, the replacement of annual energy crop production on arable land by ecological advantageous SRC could be a further goal. As governmental authorities own only small shares of land, private sector land owners need to be motivated to increase biomass supply for energetic usage. The government could stimulate the production of ecological advantageous bioenergy production by, for example, the establishment of financial incentives for landowners to shift to SRC and include landowners and further stakeholders, e.g. from nature conservation, in political strategy planning processes. Typically, participation takes place on the regional scale, where the integration of stakeholders can be most successful [Butler Manning et al., 2015]. Those political participation and

group-decision processes can be improved by using participative modelling and corresponding tools for scenario definition, modelling, and visualization. However, there is a gap between already existing paper-and-pencil DSS frameworks, simple spreadsheet-based end-user DSS and highly complex scientific bioenergy simulation systems. Stakeholders should be enabled to define and adjust scenarios participative and directly quantify and visualize the results.

The purpose of this paper is to present a methodology, modelling concept, and reference software implementation of a tool tailored to fill the described gap to support regional participation and group-decision processes for dendromass production by software-based scenario definition, quantification and visualization. Furthermore, it announces the public availability of the resulting software product under an open-source license to foster its application and to provide the software's source code as a starting point for further developments.

III.2.3. Methodology

To support regional discussion and participation processes, participatory modeling is a useful approach to assist stakeholders in visualizing the consequences of specific decisions scenarios and to help in collective decision-making [La Rosa et al., 2014, Voinov and Bousquet, 2010]. For this purpose, the development of 'Bio-Energy Assessment and Simulation Tool' (BEAST) was started in the context of the joint research project 'Strengthening Bioenergy Regions' (German: 'BioEnergie-Regionen stärken', BEST). The tool integrates ecological assessments (ecosystem functions and services) with economic calculations as a basis for regional participative dialogs and participatory modeling (Figure III.5). It considers wood from forests, open landscapes and short rotations. However, the focus is on the spatial selection of preference areas for SRC under user-defined ecological and economic restrictions and selection criteria. The BEAST uses preprocessed input data of a study region, which makes it independent from specific growth-modeling approaches; the BEAST also provides easy-to-use graphical user interfaces to define goals, restrictions and parameters for creating and analyzing scenarios of woody bioenergy utilization. The selection of preferred SRC areas is processed - in a multi-criteria evaluation - based on stakeholders' perceptions with respect to ecosystem functions and services as well as economic returns compared to certain annual field crops. The scenario results are processed for two 20-year periods: 2011 to 2030 and 2031 to 2050. This creates the possibility of incorporating climate change effects into the scenario assessment via the input data.

The BEAST system ideally complements existing approaches in the field of bioenergy modeling and participation process support, as those approaches and the BEAST can be applied side-by-side or integrated into regional participation processes. Such existing approaches comprise the following (Global Bioenergy Partnership, 2011 for list of tools; see, e.g., Milbrandt and Uriarte, 2012:

- Specific simulation models, which can serve as producers of input data for the BEAST. Examples of such models are detailed forest wood supply models [e.g., Sacchelli et al., 2013] and SRC growth models [e.g., De Groote et al., 2015, Tallis et al., 2013].
- Participation framework models, which can serve as discussion guidelines in which the application of the BEAST can be embedded, as these frameworks do not include computer simulations for (spatial) scenario visualization [e.g., FAO and UNEP, 2010, Lezberg et al., 2011].

- Related simulation approaches for identification of potential areas for production [e.g., Bauen et al., 2010, Wu et al., 2012, Aust et al., 2014], fitomass energy calculations [e.g., Bai et al., 2016], CO₂ calculations for different biomass sources [e.g., Bai et al., 2017], holistic renewable energy calculations [e.g., Benedek et al., 2018], and impact assessments of land-use changes [e.g., Meehan et al., 2013, Schulze et al., 2016] with different application domains and, therefore, without an integration into a user-friendly open-source tool applicable for participatory modeling in regional participation processes. Nevertheless, those approaches can serve as a technical basis for input generation or as a methodological basis for the extension of BEAST.

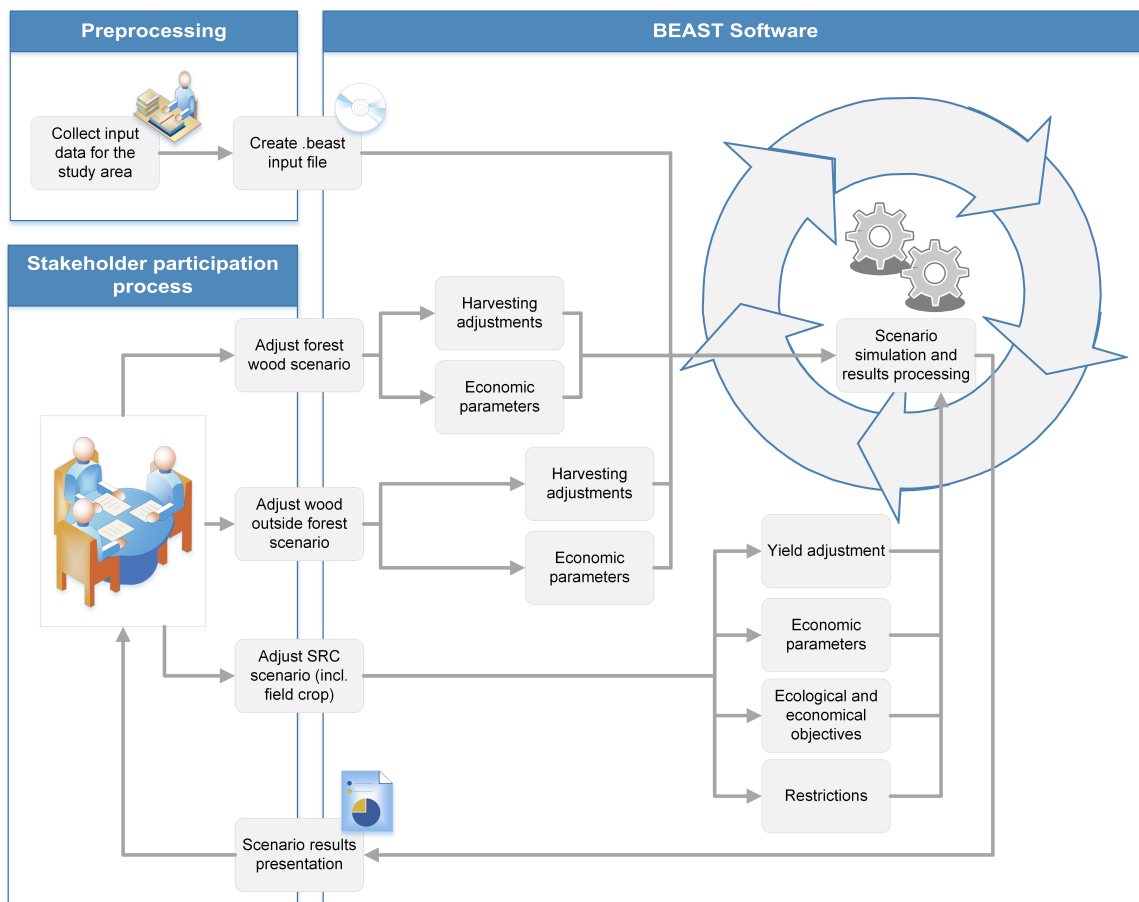


Figure III.5.: Use case visualization of the 'Bio-Energy Assessment and Simulation Tool' (BEAST). The flow chart depicts the processes of input data preprocessing, iterative software usage in the stakeholder participation process by adjusting scenario settings, and the production of simulation results. Scenario adjustments are discussed in the stakeholder workshops on the basis of the simulation results and can be immediately entered into the forms of the BEAST software to request a new scenario simulation.

A first version of the BEAST tool was applied to the Göttingen district in Central Germany. This version was far away from being applicable independently from the system developers

although the backend model system was equivalent. The results of that case study can be found in Busch and Thiele [2015]. The paper presents a methodology to generate the necessary input data and parameter values for the tool, including advice on data sources, which can be adapted for system application to other study areas. In the meantime, the software has been further developed to be applicable in participative process independently from the system developers, e.g. by adding Saaty's Analytic Hierarchy Process (AHP) [Saaty, 1990, 1987] to support the group-decision making process.

The application software development cycle followed the spiral model by developing prototypes in several iterations. The prototypes were presented in stakeholder groups of regional actors of the Göttingen district for feedbacks which have been incorporated in the next version.

The development of the upstream backend model concept followed also the spiral model. The simulation model concept was developed by interviewing domain experts, transforming the interview results into algorithmic simulation model descriptions and requesting feedback on the descriptions by the domain experts.

III.2.4. Simulation Model Concept

The simulation model concept delivers an impression of the internal processes of the BEAST software, i.e., which inputs are used and how results are processed. The description follows the ODD (Overview, Design concepts, Details) protocol for simulation models [Grimm et al., 2006, 2010].

Overview

Purpose BEAST is designed to define and evaluate scenarios of woody biomass on a regional scale. It supports stakeholder participation regarding ecological and economic aspects via participatory modeling. The system considers different sources of woody biomass and delivers biomass and energy potentials. It also discloses preference areas suitable for establishment of SRC on arable land based on multiple criteria. It enables users to compare scenario-based biomass availability to a politically targeted amount. Thus, the system identifies, for example, the necessity of political actions to foster the attractiveness of woody biomass production.

Entities, state variables and scales BEAST handles three sources of biomass: wood from forests, wood from outside of forests and SRC on arable land. For comparative purposes, field crops are also processed. Whereas wood from forests as well as from outside of forests is taken into account only as aggregated biomass pools in the system, SRC and field crops are modeled spatially explicitly on arable field geometries.

The basic state variables of the different sources are the biomass potentials.

The minimum time scale of internal processing is one year. The output is presented in two periods with lengths of 20 years each. The spatial scale of calculations for wood from forests and wood from outside forests is the study region, determined by the input data. The scale for the processing of SRC and reference field crops is the single field, determined by the input data as well. Thus, the system itself is virtually scale-independent.

Process overview and scheduling The simulation begins by loading the inputs and parameters from a selected input file and updating the parameter values using user inputs from the Graphical User Interface (GUI). Then, the simulation runs separately for the two simulation periods of 20 years each. Within a simulation period, the different biomass sources are simulated independently from each other. The biomass and energy potential from forest wood and wood from outside of forests is calculated distinctly for different compartments (forest: stem, industrial/fire wood, residues; outside of forest: stock, yield) but is spatially aggregated for the study area. In contrast, the calculations for arable reference crops and Short Rotation Coppices are performed spatially explicitly. Therefore, yield and resulting economic return are calculated for all fields. The economic return of a reference field crop rotation is calculated and compared to the economic return of SRC as an annuity difference value. This value serves as an area selection criterion in addition to other criteria or objectives, mostly ecological ones: susceptibility to (water) erosion, landscape diversity, rate of water percolation, potential nitrate leaching, area complexity, slope, soil quality index, and soil moisture index. A check of each field area against the selected restrictions and objectives is performed, as well as a calculation of the criteria sum based on criteria values, scaling and weightings is done. Then, the list of potential SRC areas is reduced to those that conform to the selected restrictions and objectives. This subset is sorted by decreasing value of the scaled criteria sum, which serves as a proxy for selection preference. Next, areas are selected as preference areas based on their criteria sums and by checking restrictions regarding the max. area of SRC within administrative and ecological units simultaneously. If the minimum distance option is selected, the minimum distance between two SRC fields is also checked by buffering and subsequent intersection test against all fields selected so far. If an intersection is found, the candidate area is rejected and not put on the list of preference areas. At the end of the SRC calculations, the areas on the preference list are further classified.

The inputs, parameters and results for all wood sources and the reference crops are aggregated and stored. If another simulation period is pending, parameters with annual change factors, i.e., yields, prices and costs, are prolonged to the next period and the next iteration is started. If the last simulation period is reached, there is an option of writing the results to a file and loading the results into the ResultsExplorer tool, which visualizes the results in tables, plots and maps.

A visualization of the process schedule is attached in Digital Supplement 5.

Model design concepts

Basic principles. The data- and model-driven system serves as a shell for scenario analysis and decision support. High flexibility and fast processing are guaranteed by using as many input data as possible from preprocessed import files. Even changing the study area by loading a different input file is a simple task. Simultaneously, the system itself is independent from yield and growth models and corresponding modeling approaches. Its rapid response to changed parameters encourages users to play with values and learn how they affect the results.

Emergence. Scenario results, especially the pattern of spatial distribution of potential SRC fields, emerge from user-defined scenario settings, such as restrictions, objectives, criteria scaling and weighting.

Objectives. The system captures and visualizes the stakeholder's perceptions of regional renewable energy goals for woody biomass.

Stochasticity. The system includes no random effects.

Observation. Figures of biomass demand and supply, primary energy equivalents and annuities are stored during the simulation for all sources of wood supply. Annuities for all field crops and crop rotation composition are also captured. Moreover, scaled criteria values, scaled criteria sums and flags reflecting (a) the fulfillment of restrictions and objectives, (b) the selection of potential SRC fields and (c) the SRC classification are stored for further analysis.

Details

Detailed descriptions of initialization, inputs, and processes are beyond the scope of this paper and can be found in the documentation accompanying the software bundle and in the online repository (<https://beast.sourceforge.io/>).

III.2.5. Software Design Principles

The following five principles guide the software design and implementation.

1. *Easy to install and use:* The target audience of the software is stakeholders in regional energy policy participation processes as well as consultants in such discussion processes. Therefore, the software needs to be easy to install and should come with a generally self-explanatory and easy-to-use GUI. The level of detail has to be selectable.
2. *Integration of ecological, political and economic aspects:* To mediate the interests of different stakeholders, the system has to integrate perceptions about different ecological, political and economic aspects of woody biomass production for energy usage.
3. *Fast output generation:* To support participation processes, the software should not only be useable in back-offices after discussion processes but also should be applicable simultaneously with the meetings. The scenario settings should be definable via the GUI and should guide the discussion. Testing and analyzing different variants of parameter adjustments should be possible during the meetings. Therefore, the processing of intensive calculations needs to be either avoided or optional in order to keep the software's response-time as short as possible so as not to interrupt discussions for too long. Instead of using equation-based modeling on demand in every scenario simulation, base data could be preprocessed, but they need to be modifiable during scenario processing.
4. *Visual result presentation and export:* To be usable in participation processes, the results should be presented visually. Because it focuses on the discussion of locations for Short Rotation Coppice, the system should present preference areas on a spatial map. Export functions could create the possibility of further analysis of results in external software, such as statistical analysis programs and Geographical Information Systems (GIS).

5. *Foster re-usage and further development*: To increase its reliability, the system should not appear as a black box, and it should come without costs and without usage of proprietary libraries in order to increase its distribution and re-usage. Furthermore, the source code should be available to allow community development and improvement of the software.

III.2.6. Implementation

The first design goal is addressed by providing ready-to-use Windows executables and by implementing a navigation tree separating and structuring the different input forms. Several supporting visualizations of input data help in finding reasonable parameter settings. Weights of criteria for multi-criteria analysis are derived from pairwise importance comparisons using Saaty’s Analytic Hierarchy Process (AHP) [Saaty, 1990, 1987]. The resulting weights are visualized in a spider diagram, and user-defined criteria scaling are given by defining support points, which are visualized in a line graph. Where possible, form entries are validated for plausibility.

The second design goal is fulfilled by implementing the described simulation model concept, which ensures that ecological and economic aspects are integrated into the assessment, thus reflecting different political goals and stakeholder perceptions.

The requirement of short response times of the scenario simulation (3rd design goal) is addressed by shifting time-consuming operations as much as possible into preprocessing, as well as by loading and changing the input data from lightweight files packaged in a single archive file with the .beast extension. Furthermore, the tool is implemented as Desktop software instead of as a Web application to ensure usability everywhere, even without Internet access.

The 4th design principle is addressed with the ResultsExplorer tool, which provides functionality to load results stored in a .beast file or immediately processed with the ScenarioGenerator tool. The ResultsExplorer produces interactive bar charts and boxplots of all ecological and economic criteria for all biomass sources. A MapViewer application is integrated into the ResultsExplorer, which provides the possibility of analyzing the inputs and results of the SRC/field crop scenario simulations spatially and of combining them with external maps from local files and/or WebMapping Services.

The software is built upon established open-source libraries and comes under an open-source license to meet the 5th design goal. As a program written in the Java language [Gosling et al., 2015], it is implemented platform-independent and executable on various platforms. Table III.1 gives an overview of the libraries used for implementing the software. BEAST is developed using the Eclipse IDE [The Eclipse Foundation, 2017] with Maven build tool [The Apache Software Foundation, 2017a] support. In conjunction with the launch4j plugin [Kowal, 2015], a full-fledged automatic production ecosystem for executables is realized. Directions for setting up the project with Maven in Eclipse IDE, as well as the source code itself, are documented in a development guide, which accompanies the usage guide and documentation.

Table III.1.: Open-source libraries used for implementing BEAST.

Library	Domain	Reference
Swing	Basic GUI components	Oracle [2015]

JGoodies	Advanced look and feel as well as form layout for Swing panels	Lentzsch [2016]
JFreeChart	Interactive and non-interactive charts including bar charts, spider web as well as box and whisker plots	Gilbert [2014]
Apache	Commons Lang Multi-language GUI support	The Apache Software Foundation [2017b]
EclipseLink	MOXy XML-file mapping	The Eclipse Foundation [2015]
Opencsv	.csv file parser	Smith et al. [2017]
GeoTools	Geoprocessing and map viewing functions	GeoTools [2016]

So far, the tool and its foundations were briefly introduced by describing the simulation model concept, the software design principles, and the implementation. The software product is available as open-source software, which is an important step towards more open and reproducible science and towards lowering the boundary between science and government by means of transparency [Pfenninger et al., 2017].

To foster re-usability, a comprehensive usage guide, documentation and development guide were added, and the software as well as its source code can be downloaded from a publically available repository (<https://beast.sourceforge.io/>). Being freely available, it can be applied to any region after input data preprocessing. Furthermore, as an open-source software, the source code can be modified, thus, the software can be extended to additional use-cases, or parts of the code can serve as starting points for different tasks with similar functional requirements.

Next, a brief impression of the software's GUIs is given (Figure III.6). A comprehensive overview can be found in the usage guide. When starting the software the ScenarioGenerator opens and the user can select a study region. The delivered software package comes with a dummy input dataset of an imaginary example region as well as with a tool to create input files from pre-processed data. The ScenarioGenerator opens the possibility to modify the default model parameters and delivers manifold options to adjust the input values, e.g. the field specific growth rates of the different field crops. Several plots visualize the input data to support such customizations of the input data. Furthermore, the constraints for the potential SRC fields as well as the selection criteria based on the AHP are defined in the ScenarioGenerator. The settings can be stored in the same or a new scenario input file.

Once the scenario is defined the simulation can be requested. Depending on the number of polygons and the settings the processing takes some seconds till some minutes. When the simulation is finished the results can be stored in the same or a new scenario file and the scenario results can be opened in the ResultsExplorer (Figure III.7). There are manifold options for analyzing the results. The interactive demand vs. supply plot shows, if the predefined demand of dendromass can be delivered under the defined scenario settings and, if so, which dendromass sources are required. The results are presented in several tables, barcharts and boxplots and can be analyzed by manifold criteria. Furthermore, they can be explored spatially with the MapViewer component (Figure III.8) and it is possible to export the data in tables and maps to be further analyzed in external software.

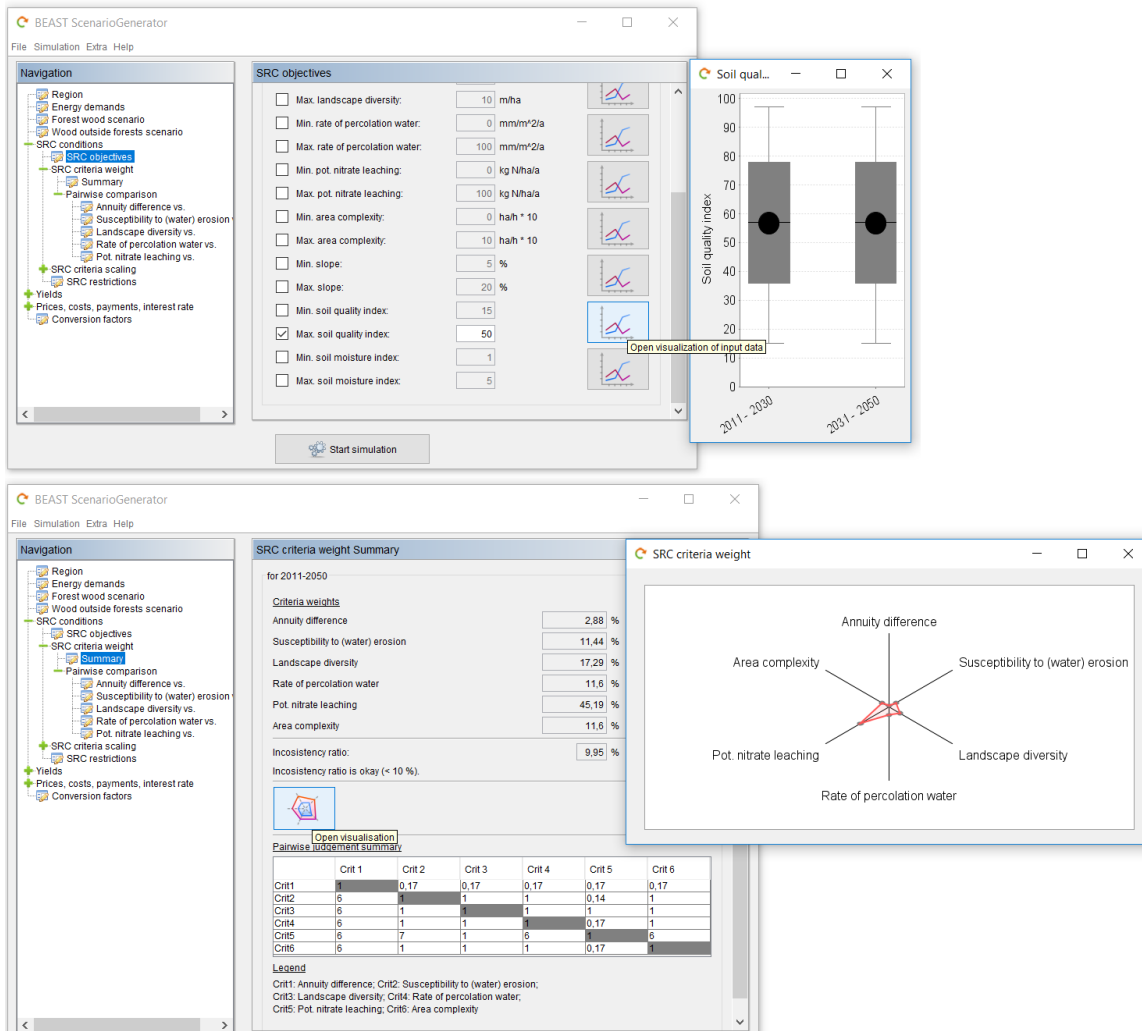


Figure III.6.: Two example views of the ScenarioGenerator of BEAST tool. On top of the figure: SRC objectives selection. Here, only field with a low soil quality (index < 50) should be selected. The plot on the right shows the distribution of the soil quality index in the study area, which is given as orientation of meaningful values. As the soil quality index of a field is assumed to be invariable over time, the value distributions are identical for both simulation periods (could be changed via the input data). On bottom of figure: The summary view of criteria weightings based on AHP. The spider graph on the right delivers a visual representation of the importance ranking of the different selection criteria. In this example, pot. nitrate leaching has the highest importance, i.e. areas which get out most of SRC regarding nitrate leaching will be prioritized.

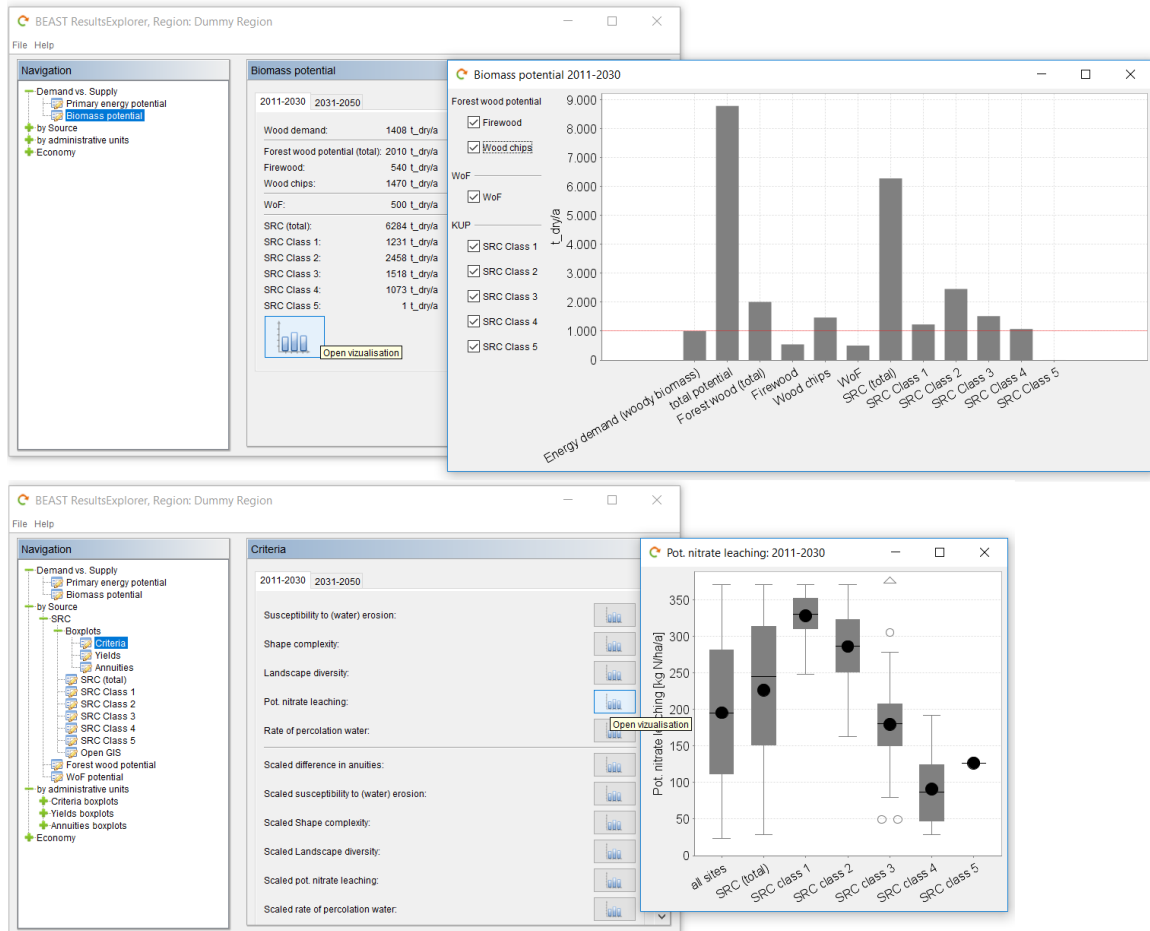


Figure III.7.: Two example screenshots of the ResultsExplorer for the example given in Figure III.6. On top the woody biomass demand is compared to the biomass potential for the selected scenario. In the figure on the right, the different sources can be switch on and off and the necessary mix of sources to meet the demand can be explored. On bottom the distribution of the pot. nitrate leaching of the potential SRC fields are given - as total over the whole study region as well as as total over all SRC preference locations and for each preference class. The effect of the high weight of this criteria is indicated by the strong decrease over the different preference classes.

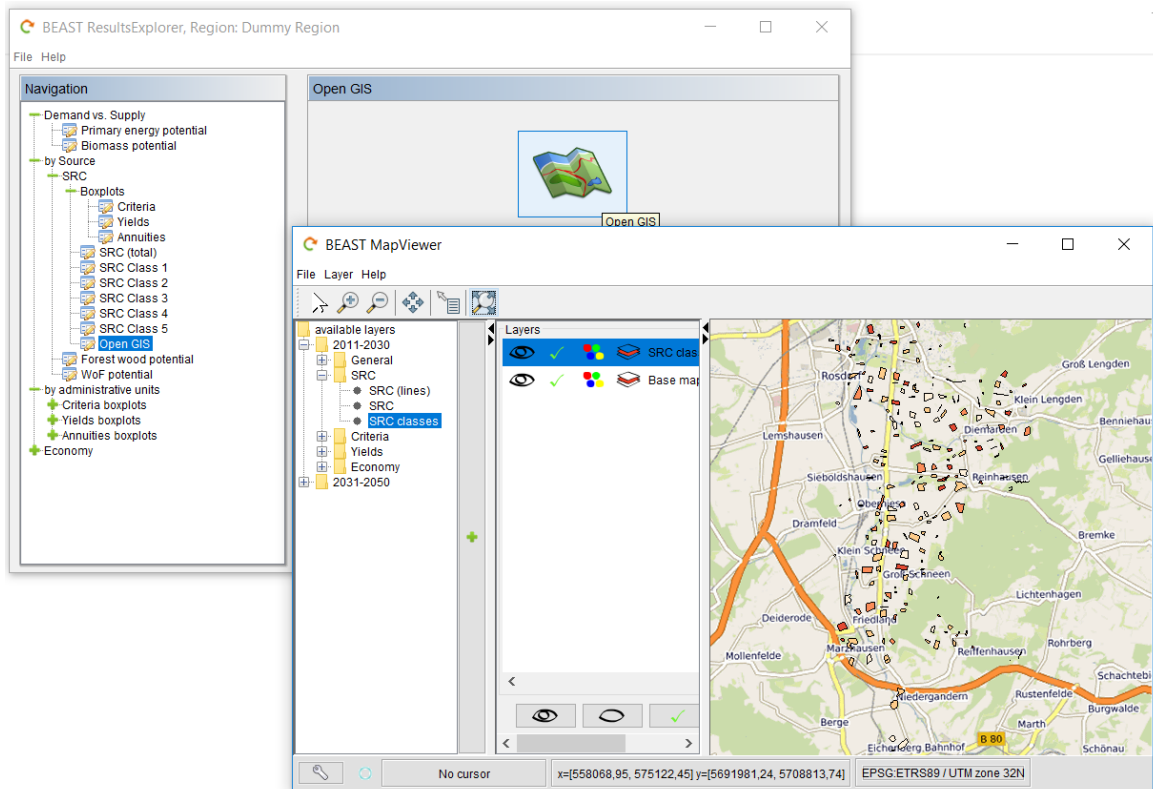


Figure III.8.: Screenshot of MapViewer to analyze the scenario results of potential SRC fields spatially. Red colored polygons indicate selected potential SRC fields. The different colors represent the different preference classes. A minimum distance between two SRC field of 100 meters was specified in the ScenarioGenerator, which explains the scattered spatial pattern.

III.2.7. Conclusion

The BEAST system presented here allows users to integrate economic returns with ecological assessments of the utilization of woody biomass on local and regional levels. It was developed to facilitate participatory scenario generation and analysis in stakeholder dialogues. During the tool's development, the concept and prototypes were presented to stakeholders, and their feedback has been incorporated into the development of the system.

The system was applied to the Göttingen district in Central Germany [Busch and Thiele, 2015]; however, the system has been implemented as a scenario simulation shell and is, therefore, generic enough to be applied to other study regions. It is possible to replace criteria sets without rebuilding the system architecture. Therefore, Hübner et al. [2016] adapted the BEAST to a second study area with a focus on landscape metrics, and a report about the general methodology is currently under review by the International Energy Agency [Busch, 2017].

Furthermore, the range of applications could be extended. For example, Bredemeier et al. [2015] and Busch [2017] used the BEAST methodology for purely scientific purposes instead of for stakeholder dialogs by running multiple scenario simulations - with cost and price values drawn from statistical distributions - as Monte Carlo simulations manually. The BEAST software could be extended to run and analyze those Monte Carlo simulations automatically. However, key factors for the long-term success of any such simulation system are continuous adaptation, improvement and support. Therefore, the system is now released under an open-source license and placed into the hands of the scientific community for usage and further development. It comes with a usage guide, documentation, and a development guide.

If governments want to foster the production and use of woody bioenergy as one key part of a renewable energy mix, first, a realistic estimation of available biomass potentials is needed, and second, governmental energy planning needs to reflect the interests of various stakeholders, such as land owners and nature conservators, which usually results in regional participation processes. Tools such as the one presented can support such political participation processes with participative modeling techniques using scenario quantifications and visualizations and, therefore, should become an integral part of such participation processes. However, even if such tools are developed in a scientific framework, as is the case with the BEAST software, they can only be successful if they do not appear as black boxes. Thus, they should always be available as open source software.

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CHAPTER IV

Information, Data and Collaboration Management in Joint Research Projects

SECTION IV.1

eResearch - Digital Service Infrastructures for Collaboration, Information and Data Management in Joint Research Projects in Ecology - An Example

This manuscript is submitted to International Journal of E-Collaboration as: JC Thiele. eResearch - Digital Service Infrastructures for Collaboration, Information and Data Management in Joint Research Projects in Ecology - An Example.

IV.1.1. Abstract

Joint research projects in Ecology typically aim to integrate scientific knowledge from various disciplines. This raises the request for collaboration technologies. Additionally, as ecological research is data-intensive it requires the management and exchange of large datasets, often with spatial reference. The demand for collaboration, data and information management tools in science is addressed by the creation of digital service infrastructures, so called eResearch Infrastructures, which are collections of - typically web-based - software systems.

Here, an example eResearch Infrastructure implemented for a joint research project is presented. It is described by the user stories, the derived functional requirements and their implementation in software systems. This infrastructure followed an open-source paradigm with only two exceptions. Based on the lessons learned recommendations for the future development of eResearch Infrastructures and their embedment in organizational, project and scientific framework are derived.

IV.1.2. Introduction

Joint research projects in Ecology, as in other field study and data intensive research areas, have manifold use cases and requirements for information, collaboration and data management. Some examples are:

- action logs on the experimental plots, like irrigation actions,
- coordination of joint measurement campaigns,
- management of carpools for driving to research fields,
- spread of information by project coordination,
- provision of base data for further data analysis,
- exchange and management of measurement data,
- validation of automatically recorded measurement data, and
- joint writing of publication manuscripts and project reports.

The need for eResearch Infrastructures for those requirements especially increases when the research teams are geographically dispersed [Siemens, 2010]. With the help of IT-systems the exchange of information and data can be made independently from time and/or location. Therefore, eResearch Infrastructures comprising collaboration, information and data management systems can deliver a substantial contribution to an efficient information and data flow in joint research projects [see, e.g., Markauskaite et al., 2012, Martin, 2014, Thomas, 2011].

Especially the task of management, provision and preservation of research data gained increasing attention since several years [Akers et al., 2014, Androulakis et al., 2009, Pinfield et al., 2014, Pryor, 2013]. Even the Organization for Economic Co-operation and Development (OECD) promotes the internet-based accessibility and preservation of research data from public funding as a key element of the research infrastructure [OECD, 2007]. In recent years, several scientific libraries picked-up the topic and are now planning to built-up

or already operate public data repositories [e.g., Cox et al., 2017, Cox and Pinfield, 2014, Tenopir et al., 2014, Corral et al., 2013, Wittenberg and Elings, 2017].

Moreover, some research funders explicitly request strategies for data management for joint research projects [e.g., German Research Foundation, 2009, National Science Foundation, 2017]. This requirement resulted in the development of several further research data repositories. Either for a specific research project [e.g., Curdt and Hoffmeister, 2015, Engelhardt, 2013, Willmes et al., 2014] or as public available repositories, such as Pangea [Diepenbroek et al., 2002, Grobe et al., 2006], DataONE [Michener et al., 2012], and Dryad [Miller, 2016, Vision, 2010]. Furthermore, in the context of biodiversity research, a microcosm of sophisticated data repositories have been set up [see, e.g., Bendix et al., 2012]. Nevertheless, as stated by Bach et al. [2012], many of these systems have been build up from scratch without the reuse of existing open-source software for data management and without the support of existing data exchange interfaces, so called harvesting interfaces, such as OIA-PMH [Open Archives Initiative, 2015] or CSW [Open Geospatial Consortium, 2016], for interconnection of repositories to build up a data network.

Data repositories are an important but only one component of an eResearch Infrastructure for joint research projects. Especially public repositories are relevant after the completion of projects for data preservation in an open data strategy. Therefore, an eResearch Infrastructure for collaboration, information and data management in ongoing projects needs more than a public data repository for long term availability.

In this paper, the view is extended to eResearch Infrastructures for academic research projects not only addressing data management and publication but targeting all tasks of collaboration, information and data management. The requirements and solutions built-up for an example joint research project is presented. First, basic information about the example project are given before the requirements for collaboration, information and data management in the context of the specific project are presented. Next, the solution implemented to address the requirements is described. At the end, a discussion and conclusion of the lessons learned as well as recommendations for future activities is given.

IV.1.3. Project context and requirements

The research project presented here as an example was called 'Strengthen Bio-Energy Regions' (German: 'Bio-Energieregionen STärken', BEST) and was funded by the German Federal Ministry of Research and Education. Its aim was to develop and test regionally adjusted concepts and system solutions of woody biomass production for energetic and material utilization under assessment of ecological and economic consequences. The project was clustered into seven thematic work areas ranging from climatology, soil science, wood material science, forestry, agricultural ecology and economics [Ammer et al., 2015]. Key indicators of the project are presented in Table IV.1. Main field studies were conducted in two areas of Central Germany complemented by large scale inventories, orthophoto recognition, laboratory trials, and computer simulations [CBL, 2015]. In the two study areas seven test fields were established where different treatments of short rotations and different reference field crops (rape seed, wheat, maize, grassland etc.) have been tested [Ehret et al., 2015, Hartmann and Lamersdorf, 2015, Seifert et al., 2015]. Meteorological and pedological measurement stations have been built up logging data in up to 5 minutes time intervals and sending the data via GSM modems once a day to the central server [Richter et al., 2015]. To support decision making in woody bioenergy production a Decision Support System was developed and implemented as a computer software [Thiele and Busch, 2015].

Table IV.1.: Project fact sheet for the joint research project BEST [data based on Forschungszentrum Waldökosysteme, unpublished].

Indicator	Value
Funding volume	~4 Mio. €
Timespan	4 years
Subprojects	31
Participating institutions	33
Resident cities of participating institutions	6
Field studies	Yes
Study sites	7
Simulation studies	Yes

For the described BEST project several requirements for a eResearch Infrastructure arose. These requirements are described in the following by user stories, which are one-sentence descriptions of what system users need [Research Data Alliance, 2014]. The user stories of project members, project management as well as further stakeholders, such as people interested in energy topics, are given in Table IV.2.

Table IV.2.: User stories.

ID	Story
I. User stories of project members	
s.1.1	I want to get informed when automatic measurements fail.
s.1.2	I want to get a fast overview over the status at the research fields to know when maintenance of measurement instruments or other activities (e.g., irrigation) are necessary.

s.1.3	I want to provide measurement data to the colleagues in a way easy for me and the colleagues.
s.1.4	I want to get base data to do my analysis.
s.1.5	I want to know, who is when at the research fields to ask for maintaining measurement instruments in case of errors.
s.1.6	I want to write a manuscript together with colleagues.
s.1.7	I want to hold project meetings without traveling.
s.1.8	I want to manage versions of software code.
s.1.9	I want to register and manage software feature requests and bugs.
II. User stories of project management	
s.2.1	I want to push up-to-date information to all project members.
s.2.2	I want to provide templates for project reports and presentations at a central point.
s.2.3	I want to collect all project report contributions from a central point.
III. User stories of external stakeholders	
s.3.1	I want to find publications about different energy topics.
s.3.2	I want to find information about project results.
s.3.3	I want to find event announcements around the project.

Based on these user stories functional requirements are derived as given in Table IV.3.

Table IV.3.: Functional requirements (with IDs) derived from user stories.

User story ID	Functional requirement description	ID
s.1.1	Receiving and parsing logging data.	f.1.1
	Validating data and detecting implausible and missing measurements.	f.1.2
	Writing and sending reports to instrument maintainers.	f.1.3
s.1.2	Receiving and parsing logging data.	f.2.1
	Storing logging data in a database for retrieval.	f.2.2
	Providing plots of measurement data for all registered project members.	f.2.3
s.1.3	Receiving and parsing logging data.	f.3.1
	Storing logging data in a database for retrieval.	f.3.2
	Querying measurement data with filter criteria and providing download of results for all registered project members.	f.3.3
s.1.4	Creating new (meta-) data entries by all registered project members.	f.4.1
	Storing base data or links to data with metadata in a central database.	f.4.2
	Querying metadata and providing download/link to base data for all registered project members.	f.4.3
s.1.5	Reading and editing table collaboratively by all registered project members.	f.5.1

s.1.6	Reading and editing documents collaboratively by a specified user group.	f.6.1
	Versioning documents.	f.6.2
s.1.7	Meeting via video conference with desktop sharing.	f.7.1
s.1.8	Versioning software code.	f.8.1
s.1.9	Registering feature requests and bugs.	f.9.1
	Managing feature requests and bugs.	f.9.2
s.2.1	Pushing messages to all registered project members.	f.10.1
s.2.2	Storing documents at a central location accessible for all registered project members.	f.11.1
s.2.3	Uploading documents to a central location by all registered project members.	f.12.1
s.3.1	Creating new publication/metadata entries in a central, public available publication database by a specified user group.	f.13.1
	Browsing publications by thematic categories.	f.13.2
	Querying publications by filter criteria.	f.13.3
s.3.2	Adding (sub-) project reports and metadata by a specified user group.	f.14.1
	Querying (sub-) project reports.	f.14.2
	Browsing (sub-) project reports by thematic categories.	f.14.3
	Providing (sub-) project reports for download.	f.14.4
s.3.3	Adding new event announcements to central database by a specified user group.	f.15.1
	Publishing event announcements from central database.	f.16.1

IV.1.4. Realized eResearch Infrastructure

The function requirements of Table IV.3 are mapped to building blocks in Table IV.4 composing the eResearch Infrastructure for the BEST project presented here as an example.

Table IV.4.: Mapping of functional requirement to building blocks of the eResearch Infrastructure.

Functional requirement	Building Block of eResearch Infrastructure
f.1.1, f.1.2, f.1.3, f.2.1, f.2.2, f.2.3, f.3.1, f.3.2, f.3.3	Data validation and visualization system
f.4.1, f.4.2, f.4.3	(Meta-) Data management system
f.5.1, f.6.1, f.6.2, f.11.1, f.12.1	Collaboration system
f.7.1	Web conference system
f.8.1, f.9.1, f.9.2	Software development tools
f.10.1	Mailing list system
f.13.1, f.13.2, f.13.3, f.14.1, f.14.2, f.14.3, f.14.4	Digital catalog and library system
f.15.1, f.16.1	Content management system
-	Single-Sign-On and self-registration solution

The selection of software products for implementing the building blocks was guided by the goal to use open-source software to have unrestricted options for adaptations to specific purposes, to have a maximum of transparency, and to be independent from specific companies policies. This rule was fulfilled except for the collaboration and the web conference system as both were available as ready-to-use central Campus wide services using proprietary solutions. Figure IV.1 provides a visual impression of the building blocks, their implementations and whether they are publicly accessible or restricted to project members during the project timespan. Short descriptions of the selected software products for the different building blocks are given in the following (see also Digital Supplement 6 for screenshots).

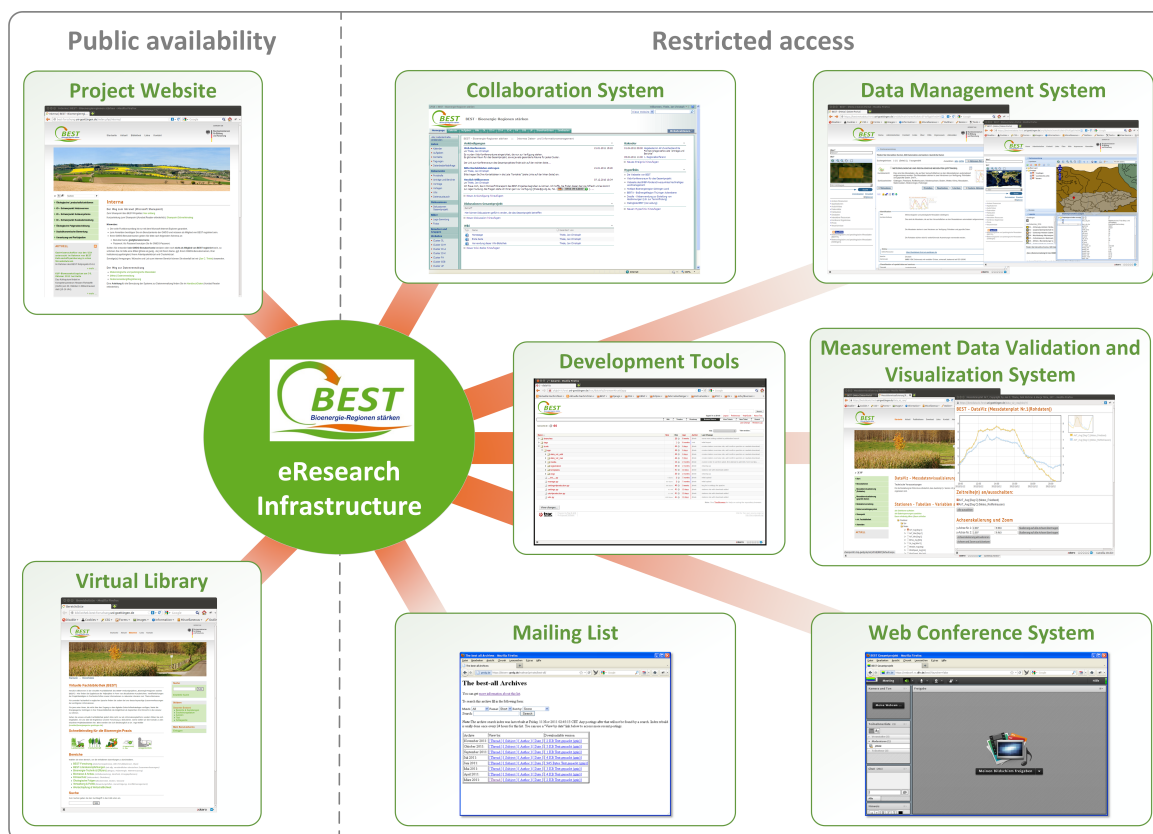


Figure IV.1.: Building Blocks with screenshots of the implemented systems of the realized eResearch Infrastructure for the BEST project. Systems open to the public are given on the left. Systems on the right are access restricted and available only for project members.

Content management system

To provide basic information to the public and act as an information and hyperlink hub a content management system (CMS) was set up for the BEST project. Furthermore, information where to find and how to use the internal data and information management systems were placed at this public CMS. The technical base was the WordPress CMS [WordPress, 2018a] enabling content editors to append, delete and change contents without programming skills using a visual editor. WordPress is published under the GNU GPL open-source

license [WordPress, 2018b]. The system contents were maintained by the project coordination office, the system was designed initially by an external web designer and hosted at the central computer service center of the University of Göttingen called Gesellschaft für wissenschaftliche Datenverarbeitung mbH Göttingen (GWDG).

Digital catalog and library system

A thematic catalogue of publications was provided to the public by building up a virtual library with all kinds of sophisticated state-of-the-art catalogue functionalities. The system was filled with metadata of and links to primary publications around the topic of bioenergy as well as with metadata and files of secondary publications and project reports. As technical base the software DSpace [DSpace, 2018a], published under a BSD open-source license [DuraSpace, 2017], in conjunction with a PostgreSQL database [The PostgreSQL Global Development Group, 2018a], published under the PostgreSQL open-source license [The PostgreSQL Global Development Group, 2018b], were selected. DSpace is a well-established web-based document repository solution used, for example, for the well-known Dryad research data repository [Dryad, 2012] as well as by various scientific libraries [see, e.g., DSpace, 2018b, DuraSpace, 2018]. Based on preconfigured themes the GUIs are highly configurable. For the BEST project the XML-based Manakin [DuraSpace, 2010] templates were used to adapt them to the project design. For publishing and maintaining contents the system provides preconfigured and adaptable workflows to highly support and guide the content administrators. By default, the underlying metadata schema in DSpace is the well-established and widely used standard Dublin Core [Dublin Core Metadata Initiative, 2012], also used in the frame of the BEST project. The DSpace repository supports several standard protocols for data exchange, such as the OAI-PMH protocol [DSpace, 2018c].

The content administration for the virtual library using DSpace was done by the Energy Agency Göttingen [Energieagentur Region Göttingen, 2018]. The system was maintained and hosted on project-owned servers.

Collaboration system

A system for web-based collaboration was realized with Microsoft Sharepoint [Microsoft, 2018]. It was selected due to its availability as a service from the central campus-wide computer service center GWDG although it does not fit into the open-source policy of the BEST project. Therefore, it was directly hosted at servers of the GWDG and not on project-owned servers. Open-source alternatives based on Wiki systems can be found, for example, at Thiele and Nuske [2008]. Only a small part of the possible functionalities of the Microsoft Sharepoint software were used in the frame of the BEST project.

Report templates as well as the collection of the report contributions of the sub-projects were handled with Sharepoint's file management and versioning functions. The calendar function was provided to plan project meetings, report deadlines and announce project-relevant conferences.

A field log book was used to record measurements on the different study fields, such as irrigation. A table for the announcement of planned visits of the study fields was used to share the cars. Furthermore, sections for the collaborative work on publication manuscripts with document check-out/check-in mechanism as well as versioning functionality were provided. Beside the section for the whole project with access and write permissions to all

project members additional sections were created to provide specific sites for the different clusters of subprojects with write permissions restricted to the cluster members.

Web conference system

Due to the circumstance that the project members were spread to six different locations in Northern Germany a web conference system with virtual conference rooms for the whole project as well as one for each cluster of subprojects were established. Although it was in contrast to the open-source policy of the BEST project, the proprietary software Adobe Connect Pro [Adobe, 2018] was used to provide video call and desktop sharing functions as it was available as an existing central national-wide service by the Deutsches Forschungsnetz [Deutsches Forschungsnetz e.V., 2017]. Therefore, the web conference system was not hosted on the project-owned servers.

Mailing list system

To push news and announcements actively to the project members a mailing list system was used. As such a system was provided as a central campus-wide service by the GWDG [GWDG, 2015] no project-specific service was implemented. The software basis of the central service was the GNU Mailman [GNU Mailman Team, 2018] available under the GNU GPL license fitting perfectly into the open-source policy of the BEST project. A web-based self-registration process was provided with a necessary approval by the list administrator.

Software development tools

For the management of software developments specific web-based tools were applied and hosted on project-owned servers. For this task, the Trac software [Edgewall Software, 2018a] was selected. Trac is a web-based project management software tailored to the development of software products that integrates version control systems and is published under a modified BSD open-source license [Edgewall Software, 2018b]. In the BEST project an Apache Subversion software system [Apache Software Foundation, 2017] was set up on the project-owned servers and coupled with the Trac instance. Furthermore, Trac includes many kinds of tools for the management of software development projects such as web-based source code browsing and searching, ticket recording and tracking, milestone planning, and wiki. Several sections/projects were set up in the Trac system for managing:

- documents, concepts and presentations,
- the customized source code of the virtual library software DSpace (see above),
- the customized source code of the (geo-) data management software GeoNetwork (see below),
- the source code of the self-written data validation and visualization system and the source code of the registration and user management system (see below), and
- the source code of the BioEnergy Allocation and Scenario Tool [BEAST, see Thiele and Busch, 2015].

The access to the Trac and Subversion systems were restricted to the software developers within the project.

(Meta-) Data management system

For the management of base and research data a catalogue and repository system was implemented. The software base used was GeoNetwork opensource [Open Source Geospatial Foundation, 2018] in conjunction with PostgreSQL [The PostgreSQL Global Development Group, 2018a] database and PostGIS spatial extension [PostGIS Project Steering Committee, 2018]. GeoNetwork opensource is released under the open-source GNU GPL license [GeoNetwork opensource, 2016] and was hosted on project-owned servers. Additionally, a GeoServer [Open Source Geospatial Foundation, 2014] instance was facilitated to provide base maps. GeoNetwork opensource is a system tailored to handle data with spatial reference. It supports catalogue standard interface OAI-PMH as well as the OGC standard conformant spatial metadata harvesting interface Catalogue Service for the Web (CSW). Thus, GeoNetwork opensource is often used to create Spatial Data Repositories as nodes of OGC conformant Spatial Data Infrastructures [see, e.g., listing at Open Source Geospatial Foundation, 2018]. Furthermore, it can handle OGC data web services: Web Mapping Service (WMS), Web Feature Service (WFS), and Web Coverage Service (WCS). By default, GeoNetwork supports two metadata standards [Open Source Geospatial Foundation, 2018]. In BEST project, the ISO19139 metadata scheme [International Organization for Standardization, 2007] was used. A web-based editor enabled the creation of new metadata entries in a web-browser including validation. Advanced search functions offered various search options including a map-based spatial bounding box search.

Data validation and visualization system

On the study sites pedological and climatological measurement stations were installed. Data loggers stored the automatic measurements. GSM modems send the measurement data once a day to a server at the University. A system was programmed which automatically validated the measurements, created and send detailed validation reports via eMail to the pedologists and climatologists. At the end of the validation process the system stored the data to a PostgreSQL database [The PostgreSQL Global Development Group, 2018a] with spatial PostGIS extension [PostGIS Project Steering Committee, 2018]. Afterwards, the data were accessible through a web-based GUI for download as well as in an on-the-fly visualization using JavaScript Flot library [IOLA and Laursen, 2014] with selection options by study field, measurement station, measured variable and date-time. In case of a download request an automatic export from the database, based on the selection criteria, was processed and the result was provided in a zip archive. The access to this web-based data usage frontend was restricted to project members. Access to an additional web-based data editing frontend was restricted to the data editors from pedological and climatological sections. Data were stored in two versions: raw data for up-to-date monitoring and corrected data approved by data administrators for further analysis.

The measurement data and validation system was developed using the Python-based web-framework Django [Django Software Foundation, 2018a], published under the open-source BSD license [Django Software Foundation, 2018b]. Additionally, a separate Central Authentication Service (CAS) system with web-frontend for self-registration and user management workflows was implemented and connected to the data validation and visualization system as well as to the GeoNetwork opensource system serving as Single-Sign-On (SSO) system. This authentication, registration and user management system was developed based on

Django-microservices django-registration [Bennett, 2018], django-cas-provider [Williams, 2017a], and django-cas-consumer [Williams, 2017b].

All components of this data validation and visualization system as well as authentication, registration and user management system were based on open-source software. The systems were hosted on project-owned servers.

IV.1.5. Discussion and Conclusion

eResearch Infrastructures are increasingly needed for the exchange of information and data. Information and data as well as their exchange are backbones of research and fundamental for the scientific progress. The establishment and usage of eResearch Infrastructures and a professional data management are increasingly requested by funding organizations [cf. Antell et al., 2014]. For such data management systems the support of standard interfaces, such as OAI-PMH or CSW, are essential key factors to build data networks and increase information and data exchange.

In this study, a system landscape from an example research project was presented that addressed the needs of a modern eResearch Infrastructure regarding external communications, collaboration and data management. However, there are several lessons learned from this example. First, it took large efforts to set up and customize the systems to the project needs. Only the collaboration support systems were available as campus-wide central services. The other systems have been set up on project-owned servers resulting in time consuming installation, programming, customizing and maintenance tasks.

In the BEST project presented here, several different software systems were implemented to fulfill all requirements. The systems variety required users to get used to the different systems that differ in handling. A more full-fledged system would be desirable, e.g., a modular system with several plug-ins for different requirements but with a common appearance and user guidance. Especially for the data management systems, where the willingness of researchers to register and provide their data is relatively low, which was also experienced in the BEST project, the reuse of the same systems in different projects would be an advantage to increase the familiarization and efficiency. This could be fostered by the above mentioned central services ensuring that the same software systems and standards are used across several projects. The payback of education investments could be maximized. In general, professional data management, knowledge about metadata standards and data networks and the value of open data should be incorporated into the curriculum of researchers' education. Additionally, funding organizations should request the openness of research data in general. Some funding organizations already support or require open access of research data [cf. Alliance of German Science Organisations, 2010, European Commission, 2017] - in the BEST project it was not required. As researchers currently often do not see an advantage in publishing their data, the usage of the data management system in BEST was low. For changing this situation, the pressure by funding organization should be increased. However, it is also important to strengthen the intrinsic motivation by providing positive incentives to motivate researchers to share their data. This could be realized by an impact factor system for publishing research data similar to journal papers. An intermediate path was already created by Journals, such as 'Biodiversity Data Journal' [Pensoft Publishers, 2018], 'Geoscience Data Journal' [John Wiley & Sons Inc., 2018] or 'Scientific Data' [Springer Nature, 2018], where researchers can publish their data with a description which is counted as a journal paper with impact factor and the possibility to become cited resulting in an increased reputation.

Furthermore, the establishment of a data management policy and a data usage agreement at the beginning of a project would ensure stronger commitment.

A further aspect increases the necessity of central services for eResearch Infrastructures and especially research data management: the long-term maintenance of the systems. Projects are typically financed for a fixed period of time. However, long-term preservation of data and the maintenance of data management platforms require long-term financing due to updates of metadata standards, harvesting interfaces and the data management and operation systems. This is a task not fixed to a projects' lifetime and can be realized most efficiently by providing central services. The example of the BEST project shows the dilemma: four years after the end of the project the servers and the software systems are not maintained anymore, the security certificates expired, the software and operation system version are outdated and the servers are down after a power failure. For the data management process the implementation of the 'embedded data manager' concept as described by Cremer et al. [2015] could be a promising approach by bridging the data management requirements in project contexts with data sharing and long-term preservation knowledge of scientific libraries.

A responsible dealing with tax money requires a changing funding regime and a strategic investment by research institutions. Fortunately, several attempts are already started, such as the eResearch support services of the eResearch pioneers from Australia [for a survey of Queensland University Libraries see Richardson et al., 2012] or the Göttingen eResearch Alliance [Dierkes and Schmidt, 2015, Dierkes and Wuttke, 2016].

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Mit Hilfe von Wikis vom Wissen aller Mitarbeiter profitieren

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IV.2.1. Zusammenfassung

Zum Arbeitsalltag gehört die Suche nach wichtigen Informationen und damit verbunden der Verlust von kostbarer Arbeitszeit. Nur selten ist das gesamte Wissen einer Organisation an einem Ort verfügbar. Wikis können beim Wissensmanagement und als flexible Kommunikationsplattform effektiv helfen. Auch im Forstsektor bieten sich zahlreiche Anwendungsmöglichkeiten. Jedoch sind die Einsatzgebiete dieser Systeme häufig unklar und die Auswahl eines geeigneten Systems im Dschungel der verschiedenen Produkte nicht immer leicht. Wikis erfreuen sich als unternehmensinterne Lösung stetig wachsender Beliebtheit. Nicht zuletzt Wikipedia hat dem Wiki-Konzept zu großer Popularität verholfen.

IV.2.2. Einleitung

Kaum jemand kann sich heutzutage bei der gemeinsamen Arbeit in Projekten oder Arbeitsgruppen der Email-Kommunikation erwehren. Dutzende Versionen gemeinsam verfasster Dokumente werden hin- und hergeschickt und füllen das Postfach. Allzu oft geht dabei die Übersicht verloren und die Suche nach dem aktuellen Dokument oder Diskussionsstand wird zur Geduldprobe. Hier können Wikis durch gemeinsam editierbare Seiten mit wiederherstellbaren Versionen Abhilfe schaffen und die Kommunikation vereinfachen. Die Projektkoordination und die Entwicklung von Ideen zur Etablierung neuer Geschäftsfelder sind so auch mit einem verstreuten Mitarbeiterstab leicht möglich.

Darüber hinaus treten in Organisationen viele Arbeitsabläufe wiederholt auf. Häufig geht kostbare Arbeitszeit dabei verloren, erneut herauszufinden wie z.B. Kunde X die Holzauhaltung wünscht, welche Vorzüge die Beschäftigung von Unternehmer Y hat und was die Naturschutzauflagen in Abteilung Z besagen. Gerade in Zeiten mit hoher Mitarbeiterfluktuation geht viel Wissen bei Personalwechseln verloren. Hier können Wikis als digitale, ständig und durch jeden (Berechtigten) aktualisierbare Wissensplattform wertvolle Dienste leisten. Als webbasierte Lösung ist ein Wiki dabei über das Internet von jedem Ort aus zugänglich.

IV.2.3. Was sind Wikis?

Namensgeber der Wikis sind die Kleinbusse am Flughafen auf Hawaii, bekannt als schnell, effektiv und preisgünstig. Mit dem Begriff Wiki (siehe Abb. IV.2) sind Websites gemeint, die ihren Benutzern erlauben, den Inhalt einzelner Seiten nicht nur zu lesen, sondern auch direkt im Browser zu bearbeiten [Ebersbach et al., 2005, Weller et al., 2007]. Im Gegensatz zu traditionellen Webseiten ist jeder Benutzer Leser und Autor zugleich (siehe Abb. IV.3). Damit ist ein Wiki eine schnell zu erlernende, leicht zu bedienende und zentral verfügbare Plattform für kooperatives Arbeiten im Internet [Alpar et al., 2007]. Viele Unternehmen nutzen Wikis [MediaWiki, 2008b, MoinMoinWiki, 2008b, SocialText, 2008, TWiki, 2008b] u.a. zur Dokumentation, als Nachschlagewerk, zur Projektplanung (siehe Abb. IV.4) oder als Diskussionsforum sowohl für einzelne Abteilungen oder Projektgruppen als auch für die gesamte Belegschaft [Majchrzak et al., 2006].

IV.2.4. Funktionalität von Wikis

Die Anwendungsszenarien deuten bereits einen Großteil der Grundfunktionalitäten von Wiki-Systemen an. Charakteristisch für Wikis sind die drei Kernfunktionen:



Abbildung IV.2.: Namensgeber der Wikis, Kleinbusse am Flughafen auf Hawaii (schnell, effektiv und preisgünstig (Quelle: [Laing, 2007])).

The screenshot shows a MediaWiki interface for a project group. At the top, there are user navigation links: 'Jthiele', 'Eigene Diskussion', 'Einstellungen', 'Beobachtungsliste', 'Eigene Beiträge', and 'Abmelden'. Below these are action links: 'Seite', 'Diskussion', 'bearbeiten', 'Versionen/Autoren', 'verschieben', and 'beobachten'. The main heading is 'Willkommen im Wiki'. The 'Einführung' section includes a link to '[bearbeiten]' and a list item: 'Startpunkt - Die allerersten Schritte im Wiki'. The 'Organisatorisches' section also has a '[bearbeiten]' link and lists: 'Aktuelle Termine', 'Adressenliste - Eine Sammlung wichtiger Adressen', 'Protokolle der Arbeitstreffen', 'Aussendarstellung - Interviews, Zeitungsartikel, Material', 'Dokumentenzentrale - hier befindet sich z.B. der Projektantrag', 'Datenaustausch', and 'Zwischenbericht'. The 'Inhaltliches' section has a '[bearbeiten]' link and lists: 'Statusseminar', 'Praxisforen', 'Politikforen - Einladung & Co', 'Übersicht über Mitbewerber', 'Mastermodell - Diskussion des Mastermodells', 'Beschreibung der Arbeitspakete', and 'Definitionen'. At the bottom left of the main content, there is a link 'Änderungsübersicht ansehen'. On the right, a circular diagram shows five stylized human figures (in blue, orange, green, red, and blue) with arrows pointing towards a central document icon labeled 'Wiki-Seite'.

Abbildung IV.3.: Hauptseite eines Projektgruppen-Wikis, realisiert mit MediaWiki.

- **Bearbeitungsfunktion:** Über eine einfache Syntax ('Wiki-Syntax') können auch Laien ohne HTML-Kenntnisse direkt im Webbrowser rasch Texte editieren. Die Bearbeitungsfunktion ähnelt dabei einem einfachen Textverarbeitungsprogramm. Nach der Bearbeitung kann die Seite als Vorschau angesehen oder direkt gespeichert werden. Gespeicherte Webseiten sind unmittelbar für alle Benutzer des Wikis sichtbar und die Änderungen erscheinen automatisch in der Versionshistorie.
- **Interne Verlinkung:** Besonders einfach gestaltet sich in Wikis die Verlinkung von Webseiten und das Einbinden von Bildern und anderen Medien.
- **Versionshistorie von Webseiten** [Leuf and Cunningham, 2001, Weller et al., 2007]: Die Aufzeichnung der Änderungen einer Wiki-Seite wird durch die Historie/Versionierung gewährleistet. Sie erlaubt es die Geschichte einer Seite zu verfolgen und vorhergehende Versionen wiederherzustellen. Zusätzlich besteht die Möglichkeit sich die letzten Änderungen in einer Übersicht anzeigen zu lassen, sodass leicht festzustellen ist, an welchem Artikel kürzlich eine Änderung vorgenommen wurde und wer sie ausgeführt hat (siehe Abb. IV.4).



Abbildung IV.4.: Versionierung im MediaWiki (links: Versionsgeschichte; rechts: Änderungsansicht)

Darüber hinaus existieren zahlreiche weitere Funktionen, die je nach Anwendungsfall von besonderem Nutzen sein können wie

- die Benachrichtigung über Änderungen im Wiki per E-Mail,
- benutzerfreundliche Editoren,
- die Auswahl von verschiedenen Sprachen,
- die Unterstützung von Umlauten und
- die Versionierung von Dateianhängen.

Gerade die Bereitstellung eines benutzerfreundlichen Editors (siehe Abb. IV.5), der die Formatierung des Textes unterstützt und direkt bei der Eingabe das Seitenlayout anzeigt, erleichtert ungeübten Computernutzern die Bearbeitung von Wiki-Seiten.

In der Testumgebung, die im Wiki Sandkasten genannt wird, kann nichts falsch oder kaputt gemacht werden. Hier besteht die Möglichkeit alle Ideen zunächst auszuprobieren. Dies senkt die Hemmschwelle, das Wiki-System tatsächlich zu benutzen.

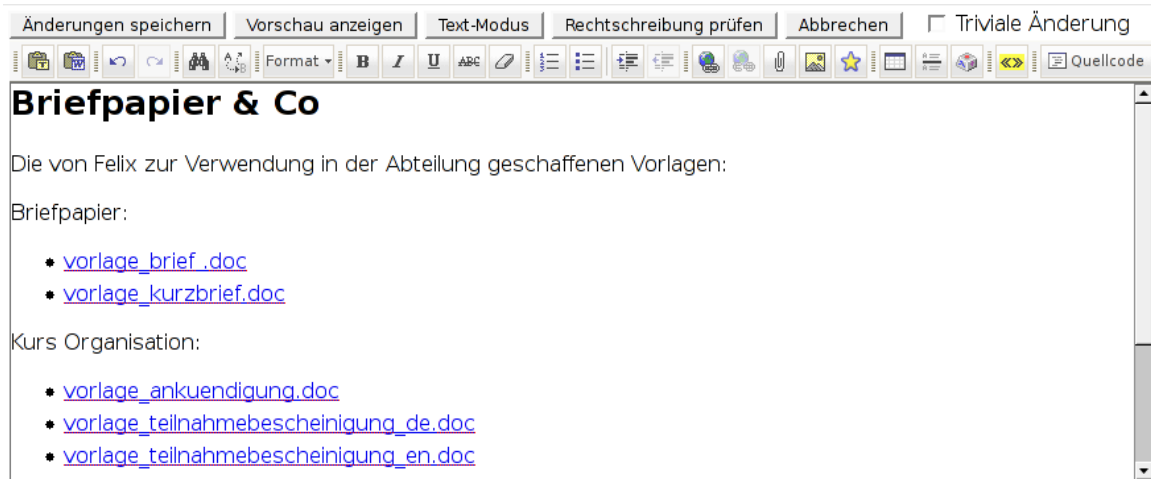


Abbildung IV.5.: Benutzerfreundlicher Editor des Wiki-Systems MoinMoin.

Auch kann es sinnvoll sein, den Zugang zu dem System zu beschränken. Hierzu bieten Wikis eine Benutzerverwaltung, die die Vergabe verschiedener Rechte an unterschiedliche Personen ermöglicht, sodass z.B. nur angemeldete Benutzer die Seiten lesen und nur die Projektmitarbeiter die Projektseite ändern können.

IV.2.5. Das soziale Phänomen

Die Möglichkeit Wiki-Seiten einfach online zu ändern, ermöglicht es mehreren Mitarbeitern auch räumlich unabhängig von einander, gemeinsam Themen und Ideen zu entwickeln. Dies stellt einen entscheidenden Vorteil gegenüber den traditionellen Techniken der Teamarbeit dar und lässt unproduktive Hierarchien schwinden. Besonders bei der Zusammenarbeit in Projekten, für deren Fortschritt Kreativität und Selbstorganisation maßgeblich sind, ist diese Kommunikationsplattform ideal. Die Teamarbeit mithilfe von Wikis ermöglicht eine weitgehend freie Zeiteinteilung, sodass die effizientesten Arbeitszeiten genutzt werden können. Dies löst zudem den Zwang, innerhalb einer gemeinsamen Teamsitzung unter konkretem Zeitdruck kreative Ideen entwickeln zu müssen, was zwangsläufig Blockaden hervorruft.

Durch die mit einem Wiki geschaffene Arbeitsatmosphäre und die Identifikation mit der Thematik durch die direkte Integration aller Beteiligten kann ein gruppendynamischer Prozess aktiviert werden, der zu einer gesteigerten Produktivität und besseren Ergebnissen führt als herkömmliche Techniken der Projektarbeit.

In Unternehmen eignen sich Wikis am besten für Situationen, in denen alle Beteiligten gemeinsam und ohne Hierarchie oder komplexe Arbeitsabläufe an einem kreativen oder dokumentarischen Projekt arbeiten. Sie können damit helfen, Arbeitsabläufe zu vereinfachen, zu beschleunigen oder eine gemeinsame Wissensbasis aufzubauen und dabei die Zahl kostspieliger Sitzungen zu reduzieren.

IV.2.6. Beispiele von Wiki-Systemen

Wikipedia hat dem Wiki-Konzept zu großer Popularität verholfen, aber neben dem MediaWiki gibt es noch über 100 weitere Wiki-Systeme [Wiki Matrix, 2008]. Zu den beliebtesten Wikis für den Einsatz in Unternehmen zählen das TWiki, die aktuell von Wikipedia verwendete Software MediaWiki und das in Python geschriebene Wiki MoinMoin. Diese drei Systeme wurden von den Autoren getestet und für unterschiedliche Zwecke produktiv eingesetzt (siehe Tab. IV.5).

Tabelle IV.5.: Übersicht über die drei populärsten Unternehmens-Wikis.

	MediaWiki	MoinMoin	TWiki
Website	www.mediawiki.org	www.moinmo.in	www.twiki.org
Version	1.12.0 (21.3.2008)	1.7.0 (21.6.2008)	4.2.0 (22.1.2008)
OpenSource	Ja (GPL)	Ja (GPL)	Ja (GPL)
Programmiersprache	PHP	Python	Perl
Datenspeicherung	Datenbank	Dateisystem	Dateisystem
abschnittsweises Editieren	+	-	Plugin
Kommentierung	Diskussionsseite	Plugin	blogartig
Benutzerfreundlicher Editor	Plugin	+	+
Änderungshistorie	+	+	+
Vergleich von Versionen	+	+	+
Historie der Anhänge	+	-	+
PDF-Export	Plugin	Plugin	Plugin
Zugangskontrolle	o	o	+
Deutsch/Sprachen	Ja/ >80	Ja/ > 30	Ja/>15
Scripting	-	-	+

Erläuterung: + gut, o zufriedenstellend, - schlecht;

Plugin: Funktionalität steht in einem Plugin zur Verfügung.

- Bei dem **MoinMoin** Wiki [MoinMoinWiki, 2008a] handelt es sich um ein sehr schlankes, in der Programmiersprache Python realisiertes, System. Die Software steht unter der OpenSource Lizenz GPL und ist damit kostenfrei verfügbar. Die Speicherung der Inhalte erfolgt in Textdateien. Dies vereinfacht die Installation des Systems, da keine Datenbank eingerichtet werden muss. Die Regelung des Zugangs für unautorisierte Nutzer ist bei diesem Wiki, wie in den meisten Wiki-Systemen, durch Einrichtung einer Benutzergruppe mit Leserechten möglich. Für einzelne Seiten oder Gruppen von Seiten können die Zugriffsrechte sehr detailliert vergeben werden. Angenehm ist, dass es schon in der Standardausführung einen benutzerfreundlichen Editor mitbringt. Alle in einem modernen Wiki üblichen Funktionen werden von MoinMoin bereitgestellt. Die Anzahl der zur Verfügung stehenden Plugins ist allerdings bisher im Vergleich zu anderen Wikis eher klein.
- Das **MediaWiki** [MediaWiki, 2008a] ist die Software mit der Wikipedia betrieben wird. Auch sie steht unter der OpenSource Lizenz GPL und ist damit frei verfügbar. Dieses Wiki-System kann auch sehr große Projekte mit Millionen von Seiten gut verwalten. Es verfügt dementsprechend über einen größeren Funktionsumfang, allerdings vor allem für lexikalische Projekte. MediaWiki ist in PHP programmiert und speichert seine

Inhalte in der relationalen Datenbank MySQL. Damit ist die Einrichtung dieses Wikis aufwendiger als die von MoinMoin. Ein Vorteil von MediaWiki ist das bereits von Wikipedia bekannte Erscheinungsbild, welches oft den Einstieg in eine neue Arbeitsweise erleichtert. Besonders bei der Beteiligung von Personen mit geringen Computerkenntnissen ist darin ein sehr großer Vorteil zu sehen.

- Das **TWiki** [TWiki, 2008a] wurde für den Einsatz in Unternehmen entwickelt und ist eines der ältesten, umfangreichsten und damit auch komplexesten Wikis. Ebenso wie die beiden vorhergehenden Systeme steht auch diese Software unter der freien Lizenz GPL. Programmiert ist TWiki in der Programmiersprache Perl und verzichtet, wie schon MoinMoin, durch die datei-basierte Speicherung der Inhalte auf eine Datenbank. TWiki besitzt eine fein abstimmbare Zugangskontrolle mit Lese- und Schreibrechten für Benutzer und Gruppen. Die Standardinstallation umfasst bereits einige Erweiterungen, wie eine ansprechendere Tabellendarstellung und einen benutzerfreundlichen Editor. Zur Anpassung an die speziellen Anforderungen für den Einsatz in Unternehmen steht eine sehr große Menge an ausgereiften PlugIns zur Verfügung. Diese ermöglichen zum Beispiel Tabellenkalkulation, Flussdiagramme und ToDo-Listen. Der im Vergleich zu den beiden anderen Wikis große Aufwand der Einrichtung wird sich meist nur bei größeren Vorhaben rentieren.

IV.2.7. Etablierung eines Wikis

Bei der Etablierung von Wikis in Unternehmen sollte überlegt und strukturiert vorgegangen werden, da spätere Korrekturen nur mit großem Aufwand durchgeführt werden können. Die Einführung eines Wikis sollte in den drei Phasen 'Planung', 'Prototyp' und 'Produktion' erfolgen [Alpar et al., 2007].

Zunächst stellt sich die Frage nach der am besten geeigneten Wiki-Software. Hier spielen zum einen die Informations- und Kommunikationskultur im Unternehmen sowie der Ziel und Zweck des Wikis eine Rolle, zum anderen die technischen Voraussetzungen und Fähigkeiten im Unternehmen [Alpar et al., 2007].

Wikis sind preisgünstige Wissensmanagement-Systeme, da die meisten Wikis OpenSource Software und damit kostenfrei sind. Jedoch verursachen auch die Installation und der Betrieb des Wikis Kosten, die bei der Entscheidung berücksichtigt werden müssen. Wird der Internetauftritt des Unternehmens auf eigenen Servern und von fachkundigem Personal gepflegt, kann auch das Wiki selbst betrieben werden. Wenn viele spezielle Funktionen oder sogar Anpassungen des Wikis gewünscht sind, ist die Verwendung von TWiki und die Vergabe eines Entwicklungs- und Beratungsvertrages zu überlegen.

- Wird das Wiki-System **auf eigenen Servern** selbst betrieben, sollte beachtet werden, dass die Anforderungen der Wiki-Software mit der bestehenden Infrastruktur harmonieren (Betriebssystem, Webserver, Programmiersprache und Datenbank) [Ebersbach et al., 2005].
- Soll das Wiki **von einem Dienstleister** (wie zum Beispiel: wikiservice, wikidev, social-text) professionell betrieben werden, sollte auf die Speicherkapazität, Datensicherung und -sicherheit, Anpassbarkeit des Layouts und sichere Übertragungsprotokolle geachtet werden [Alpar et al., 2007, Lange, 2007].

- Ein preiswerter Mittelweg ist der Betrieb eines Wikis bei einem bekannten **Webhoster** (wie zum Beispiel Host Europe, domainFactory und 1&1), als so genannte 1-Klick-Installation für 3 bis 10 Euro pro Monat, wenn gewisse technische Kenntnisse vorhanden sind [Bager, 2008, Bleich, 2008].

Generell muss die Etablierung eines Wikis durch eine Reihe von Maßnahmen unterstützt werden. Greifen diese Aktivitäten, wird das System schnell von Mitarbeitern akzeptiert und angenommen. Ein besonders wichtiger Punkt bei der Einführung von Wikis ist die Motivation der Mitarbeiter, die neuen Möglichkeiten zu nutzen, denn davon hängt in erster Linie der spätere Erfolg des Systems ab.

Ein Wiki ist zunächst lediglich eine Plattform. Der Mehrwert entsteht erst durch den aktiven Einsatz der Benutzer, welcher zunächst aktiviert werden muss. Um den Einstieg zu erleichtern, sollten zukünftige Inhalte soweit als möglich vorstrukturiert sein. Am Besten werden schon im Prototyp erste Seiten für Arbeitsgruppen, Projekte oder sonstige Themen eingerichtet, da die meisten Wiki-Nutzer zunächst Änderungen an bestehenden Seiten vornehmen, bevor sie sich an die Kreation neuer Seiten heranwagen [Alpar et al., 2007, Majchrzak et al., 2006].

Eine weitere Herausforderung stellt die Technik und die Komplexität des Wikis dar. Auch wenn die Funktionsweise eines Wikis recht simpel ist, kann sie nicht von jedem sofort verstanden und effektiv eingesetzt werden. Um die Ängste vor der neuen Technik oder etwas falsch/kaputt zu machen abzubauen, sollte den Mitarbeitern eine Dokumentation zur Verfügung stehen und eingangs eine Schulung stattfinden, in der die Funktionsweise und die grundlegenden Funktionen erläutert werden. Die oft mangelnde Motivation der Mitarbeiter zu Beginn hat häufig technische Ursachen. Gerade für Wiki-Anfänger ist daher die gute Bedienbarkeit des Systems ein Muss.

Mangelnde Beteiligung der Mitarbeiter und schlechte Strukturierung der Inhalte sind die häufigsten Punkte, die beim Einsatz von Wikis in Unternehmen Probleme bereiten. Egal, ob ein Wiki zunächst nur von einigen wenigen Mitarbeitern genutzt wird oder gleich das bestehende Intranet ersetzt, kooperatives Arbeiten funktioniert nur, wenn ein gemeinsames Ziel verfolgt wird und sich die Beteiligten darüber auch im Klaren sind [Ebersbach et al., 2005].

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SECTION IV.3

GeoNetwork - Der digitale Kartenschrank. Metadatenverwaltung für räumliche Informationen

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Authorship

- Robert S. Nuske edited the initial draft of the manuscript.

IV.3.1. Zusammenfassung

Kaum jemand käme auf die Idee sämtliche Regale einer Bibliothek nach einem bestimmten Buch zu durchsuchen, denn dafür gibt es Karteikästen oder Computer mit digitalen Katalogen. Nach Eingabe von Titel, Autor oder Themengebiet erhält man die Signatur sowie den Standort und kann gezielt das Buch aus dem entsprechenden Regal ziehen. Und wie finden Sie einen bestimmten (Geo-) Datensatz auf ihrem Computer? Eine Suche nach dem Dateinamen führt meist nicht zum gewünschten Ergebnis, wenn z.B. alle Dateien gefunden werden sollen, die mit einem bestimmten Gebiet in Verbindung stehen. Hierbei kann ein so genannter Metadatenkatalog helfen. Die Open Source Software GeoNetwork, entwickelt bei der UN/FAO, bietet hierfür ein umfassendes und komfortables System zur standardkonformen Metadatenverwaltung.

IV.3.2. Einleitung

Die meisten Daten, die von Forstbetrieben gesammelt und ausgewertet werden, wie z.B. Standortkartierung, Forsteinrichtungsdaten, waldbauliche Planung, Wegenetz, Holzernte- und Bestandespflegemaßnahmen, Naturschutzauflagen und Eigentumsverhältnisse stehen mit einem Ort in Zusammenhang. Durch die kartenhafte Darstellung gewinnen diese Daten wesentlich an Informationsgehalt.

Sowohl in den Forstverwaltungen und -betrieben als auch in den Forstwissenschaften hat sich über die Jahrzehnte ein beträchtlicher Bestand an räumlichen Informationen angesammelt. Ohne ein wohlüberlegtes Konzept zur Datenhaltung sowie zur Datenverwaltung geht dabei schnell die Übersicht verloren. Daher ist das Anlegen und Verwalten von sog. Metadaten, d.h. Beschreibungen der eigentlichen Daten, unerlässlich. Zur Verwaltung dieser Metadaten gibt es - ähnlich zu den digitalen Bibliothekskatalogen - Programme, die diese Aufgabe für Geodaten übernehmen. Beispiele sind der terraCatalog [ConTerra, 2008], der OpenCatalogue [OpenCatalogue, 2008], und das sehr weit verbreitete Projekt GeoNetwork [GeoNetwork, 2008]. Alle drei basieren auf dem OGC Standard für Catalogue Services [Voges and Senkler, 2008]. Da GeoNetwork schon weite Verbreitung gefunden hat und als Open Source Projekt (GPL) kostenfrei verfügbar ist, werden wir es hier vorstellen [GeoNetwork, 2008, Ticheler and Hielkema, 2007].

IV.3.3. Metadaten - Warum und Wie?

Warum das Anlegen und Verwalten von Metadaten so wichtig ist, hat vermutlich jeder bereits einmal erlebt. Wenn zum Beispiel Verzeichnis- oder Dateinamen nicht selbsterklärend sind, müssen gegebenenfalls unzählige Dateien geöffnet werden, um den gesuchten Inhalt zu finden. Ist bei einem Geodatensatz nicht angegeben in welchem Referenzsystem die Koordinaten verortet sind, ist unter Umständen der gesamte Datensatz wertlos. So finden sich viele weitere Beispiele, die sehr anschaulich zeigen, dass Daten, die langfristig und personen- sowie fachübergreifend nutzbar sein sollen, eine Beschreibung ihrer selbst erfordern.

Metadaten sind 'Daten über Daten'. Sie sollen darüber Auskunft geben, 'wer', 'wo' über 'welche' Daten verfügt und so das Auffinden von Informationen vereinfachen. Sie ermöglichen außerdem durch ihren informativen Charakter die Vermeidung redundanter Datenerfassung, die Aufdeckung vorhandener Lücken in den Datenbeständen, die Vereinheitlichung

von Daten und Begriffen, die Qualitätssicherung für die Datensätze und den Vergleich zwischen alternativen Datenbeständen.

Damit solche Datenbeschreibungen möglichst vollständig sind und durch viele Programme automatisch verarbeitet werden können haben sich einige Organisationen mit der Entwicklung von Standards für Metadaten befasst. Drei bedeutende Standards für Geodaten sind:

- der ISO 19139 von der International Standards Organization (ISO),
- der Dublin Core von der Dublin Core Metadata Initiative und
- die Standards des Federal Geographic Data Committee (FGDC).

Alle drei Standards werden von GeoNetwork unterstützt [Hielkema and Ticheler, 2007]. Für jeden in GeoNetwork erfassten Datensatz wird ein beschreibender XML-Datensatz angelegt. Dieser enthält eine standardisierte Beschreibung des thematischen Inhalts, der geographischen Position, des Bearbeiters (Zuständigkeit) sowie des Referenzsystems und des Maßstabs und der Qualität. Darüber hinaus werden für die langfristige Nutzung der Daten wichtige Informationen wie die Aktualität, die zeitliche und räumliche Gültigkeit der Daten und die Zugangsmöglichkeiten dokumentiert.

IV.3.4. Einrichtung und Betrieb

GeoNetwork wurde ursprünglich als ein internetbasiertes System entwickelt, es kann jedoch ebenso gut als Desktop-Anwendung mit einem ausschließlich lokal operierenden Server und natürlich in geschlossenen Netzwerken betrieben werden. Auch beim webbasierten Betrieb ermöglicht die umfangreiche Nutzer- und Zugriffsrechteverwaltung eine genaue Kontrolle der Freigaben. Damit lässt sich für nahezu jedes vorstellbare Anwendungsszenario eine Lösung mit GeoNetwork finden. Die Konfiguration von GeoNetwork ist dank des mitgelieferten Programms GeoNetwork Administration Survival Tool (GAST) denkbar einfach.

Nach erfolgreicher Installation von GeoNetwork kann die Startseite (Abb. IV.6) des nun zur Verfügung stehenden Portals über einen Webbrowser aufgerufen werden. Eine Anpassung des Layouts von GeoNetwork durch Einfügen eines eigenen Logos oder durch eine komplette Umgestaltung der Oberfläche ist möglich.

In der an GeoNetwork angebundene Datenbank werden die Metadaten gespeichert. Diese enthalten einen Verweis auf die Datensätze selbst. Somit können die beschriebenen Datensätze an verschiedenen Speicherorten vorgehalten werden. Die Daten können auf demselben Computer gespeichert sein, sie müssen es aber nicht. In GeoNetwork kann ein direkter Link zu den Daten vorliegen oder lediglich die Metainformationen mit einer Beschreibung bei wem die Daten zu erhalten sind. Darüber hinaus bietet GeoNetwork die Möglichkeit zum sog. „harvesting“, was bedeutet, dass andere GeoNetwork-Quellen in das eigene Portal eingebunden werden können, wie zum Beispiel die sehr umfangreichen öffentlichen Angebote der FAO [FAO, 2008].

IV.3.5. Funktionalität

GeoNetwork ermöglicht den schnellen und einfachen Zugang zu Geoinformationen. Datensätze, Karten und Satellitenbilder können einfach ermittelt, identifiziert und gesucht, aber auch abgerufen, kombiniert und verwaltet werden.

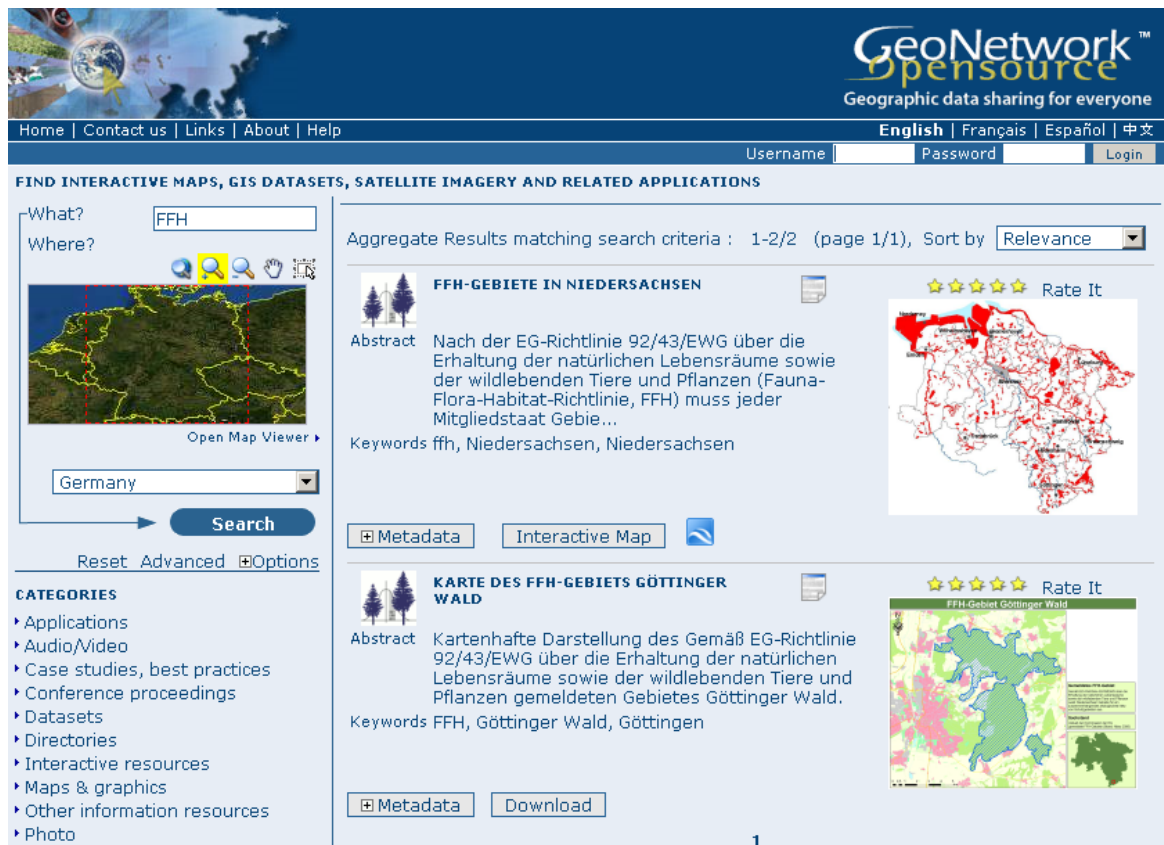


Abbildung IV.6.: Startseite von GeoNetwork.

Herzstück der Funktionalität von GeoNetwork ist die Suche. Das schnelle Auffinden einzelner Datensätze in einer sehr großen Anzahl von Einträgen wird in GeoNetwork durch ein mächtiges Indizierungssystem ermöglicht. Die Suchoptionen sind dabei sehr vielfältig und reichen von der Suche in einzelnen Feldern über eine Freitextsuche bis hin zur geographischen Suche. Die geographische Suche ist eine Besonderheit von GeoNetwork. Sie liefert alle Datensätze (inklusive der extern eingebundenen) die innerhalb eines Rechtecks liegen. Dieses Rechteck kann durch Koordinaten bestimmt oder in einer Karte ausgewählt werden (Abb. IV.7).

The screenshot displays the search interface of GeoNetwork. At the top, a header reads "FIND INTERACTIVE MAPS, GIS DATASETS, SATELLITE IMAGERY AND RELATED APPLICATIONS". The interface is divided into three main sections: "WHAT?", "WHERE?", and "WHEN?".

- WHAT?:** Includes input fields for "What?" (containing "FFH"), "Title", "Abstract", and "Keywords". Below these are checkboxes for "Map type" (Digital, Interactive, Hard copy, Downloadable) and "Search accuracy" (Precise, Imprecise).
- WHERE?:** Features a map of Europe with a yellow bounding box. The bounding box coordinates are: lat (min) 55.056, long (min) 2.6675, lat (max) 47.352, and long (max) 18.153. Below the map, there are dropdown menus for "Type" (set to "Region") and "Region" (set to "Germany").
- WHEN?:** Includes radio buttons for "Anytime" and "From" (with calendar icons) and "To" (with calendar icon). Below this is a "Restrict to" section with dropdowns for "Catalog" and "Category" (both set to "- Any -"). An "Options" section includes "Sort by" (set to "Relevance"), "Hits per page" (set to "10"), and "Output" (set to "Full").

At the bottom right, there is a large blue "Search" button, and below it, smaller links for "Reset" and "Hide advanced options".

Abbildung IV.7.: Suche in GeoNetwork.

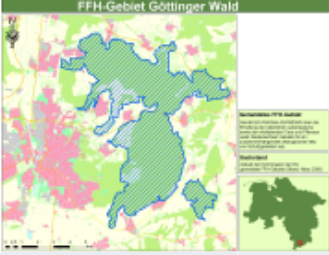
Zur Eingabe von Metadaten bietet GeoNetwork einen komfortablen Editor (Abb. IV.8). Die auszufüllenden Eingabefelder ergeben sich aus den Metadatenformaten, die der Betreiber des Portals ausgewählt hat. So können Eingabeformulare mit Feldern, die die oben genannten Standards erfüllen, verwendet oder eigene Anpassungen vorgenommen werden. Es kann zum Beispiel ein Standardformat um eigene Felder, die für das Projekt wichtig erscheinen, ergänzt oder die Anzahl der Pflichtfelder verringert werden.

Darüber hinaus bietet GeoNetwork mit der Funktion 'InterMap Viewer' eine interaktive Karte. Mit InterMap können die Geodaten direkt als digitale Karten visualisiert und sogar Geodaten aus verschiedenen Quellen in einer Karte kombiniert werden. Dabei setzen die Entwickler von GeoNetwork auch hier auf ein Höchstmaß an Kompatibilität und unterstützen daher die Einbindung von OGC-konformen Kartendiensten (Web Map Service, WMS) sowie den direkten Zugriff auf ESRI's ArcIMS. Damit bietet GeoNetwork über die Metadatenverwaltung hinaus fast alles aus einem Guss, was zum Aufbau einer Geodateninfrastruktur (GDI) nach den Richtlinien des OGC benötigt wird [Rose, 2004].

IV.3.6. Erfolgsgeschichte von GeoNetwork

Begonnen wurde mit der Entwicklung von GeoNetwork im Jahre 2001 bei der *Food and Agriculture Organization* (FAO). Ziel war dabei die Entwicklung eines Katalogsystems zur systematischen Archivierung und Veröffentlichung von Geodaten. Im Jahre 2003 beteiligte sich das *World Food Programme* (WFP) an der Entwicklung der Software und die erste Version wurde veröffentlicht. Ein Jahr später trat zusätzlich noch das *UN Environment Programme* (UNEP) dem Projekt bei. Inzwischen ist GeoNetwork ein anerkanntes Projekt der Open Source Geospatial Foundation (OSGeo) [OSGeo, 2008] und bei vielen weiteren großen Organisationen im Einsatz [Ticheler and Hielkema, 2007], wie z.B. der *Consultative Group on*

Reset Save Save and close Check Thumbnails Cancel



Identification info *

Title * Karte des FFH-Gebiets Göttinger Wald

Date * 2008-11-11T15:57:00

Date Type * Publication

Edition 1.0

Presentation Form mapDigital

Abstract *
Kartenhafte Darstellung des Gemäß EG-Richtlinie 92/43/EWG über die Erhaltung der natürlichen Lebensräume sowie der wildlebenden Tiere und Pflanzen gemeldeten Gebietes Göttinger Wald.

Purpose Kommunikation

Status completed

Abbildung IV.8.: GeoNetworks Metadaten Editor.

International Agricultural Research (CGIAR), der European Space Agency (ESA), dem US Federal Geographic Data Committee (FGDC) und der Infrastructure for Spatial Information in Europe (INSPIRE). Somit steht hinter der Software GeoNetwork ein starkes, zuverlässiges Team, das Kontinuität und Qualität gewährleistet.

Inzwischen gibt es diverse Erfahrungsberichte zum Einsatz von GeoNetwork. Eines ist das 'RuhrGIS' für das Metadatenmanagement kommunaler Geodaten [RuhrGIS, 2008]. Das Portal von RuhrGIS dient dabei vor allem der standardkonformen Dokumentation von Geodaten, der Information der Öffentlichkeit und Wirtschaft und der komfortablen Suche nach Datenbeständen über räumliche oder fachliche Filterkriterien.

Aus dem Bereich der Forschung tritt besonders das Projekt „Hof Ritzerau“ in Erscheinung [Hoernes and Roweck, 2007]. Ziel des Einsatzes von GeoNetwork in diesem Forschungsprojekt ist es, alle erhobenen Daten und Ergebnisse auch über den Projektzeitraum hinaus für alle Projektmitglieder verfügbar und nachvollziehbar zu halten. Dazu werden sämtliche Geodaten auch in diesem Projekt nach einer erweiterten Version des internationalen Metadatenstandards ISO 19139 dokumentiert.

IV.3.7. Empfehlungen

GeoNetwork bietet mit seinem Funktionsumfang und seinen flexiblen Einsatzmöglichkeiten auch für den Forstsektor ein großes Optimierungspotential bei der Verwaltung von Geodaten. Nicht nur Vektor- und Rasterkarten können mit dieser Software archiviert werden, sondern sämtliche Daten, die einen räumlichen Bezug haben. Das kann zum Beispiel auch Excel-Tabellen umfassen, wenn ihnen eine Koordinate zugeordnet werden kann. So lassen sich dann auch alle Excel-Tabelle finden, die innerhalb eines vom Benutzer bestimmten Gebietes liegen. Somit können und sollten für sämtliche Daten, für die ein räumlicher Bezug hergestellt werden kann, ein Metadatensatz mit GeoNetwork angelegt und verwaltet werden.

Für den Betrieb einer lokalen Einzelplatz-Anwendung von GeoNetwork unter Windows stehen entsprechende Installationsprogramme auf der Internetseite von GeoNetwork bereit [GeoNetwork, 2008]. Diese Installation kann auch mit geringen Computerkenntnissen durchgeführt werden. Für den Betrieb als Internetplattform sind hingegen vertiefte Computerkenntnisse in den Bereichen Datenbankmanagement, Webserverkonfiguration und -absicherung notwendig. Hierfür sollten ggf. Spezialisten hinzugezogen werden. Nach erfolgreicher Installation und Konfiguration ist das Portal aber auch mit geringen Computerkenntnissen nutz- und erweiterbar.

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Discussion and Outlook

The present thesis was motivated by the practical needs of researchers, politicians, farmers, and foresters for information generation and management using Environmental Information Systems. It aimed to contribute to the development of methodological and technical solutions for the application of Environmental Information Systems to current topics in environmental management by scientific means to support decision making in practice, to uncover further research needs and to provide prototypes and best practices.

This has been done on the basis of three examples, two in the field of model- and data-driven Environmental Decision Support Systems and a third one by developing a supporting eResearch Infrastructure combining several Environmental Information System tools from the fields of collaboration systems and (spatial) data management. The research agenda was inspired by the Design Science methodology [Hevner et al., 2004], by building and evaluating IT artifacts as a pragmatic approach to solve real-world problems. This research methodology is often applied in the field of Information Systems.

This concluding discussion and outlook summarize the achievements of the thesis, draw the lessons learned, embed them into the surrounding research progress and strive the light on open issues for further research.

V.1. Lessons learned

The DSS-WuK system was developed to assess the impact of climate change to German forests and to support an adopted tree species selection. It is a web-based, spatial data- and model-driven Decision Support System. The BEAST system was developed to support group decision making and potential analysis in strategic regional (woody) bioenergy planning processes and area selection for the siting of Short Rotation Coppices. It has been developed as a standalone, spatial data- and model-driven, Multi-Criteria Decision Analysis (MCDA) based Decision Support System. The eResearch Infrastructure was developed as a web-based collaboration and data management system supporting data, information and knowledge management.

Open source software Common to all these systems is that they are implemented on the basis of existing open source software libraries, with exception of the Microsoft Sharepoint

collaboration system and the Adobe Connect video conference system. The advantage of using existing libraries is that many functions must not be coded from scratch, and the code quality as well as security is potentially higher when libraries are maintained by a community of several programmers. The resulting systems BEAST, DSS-WuK, DataViz, and CAS are distributed themselves under an open source license (Digital Supplement 7). Open source licensing is an important feature of scientific software as it makes it possible to reproduce and trace results. Furthermore, it has the potential to increase the transparency and reliability of Information Systems. Moreover, it can be maintained and further improved by others. This is a very important feature as Information Systems initiated during research projects are often missing long term funding. Releasing those software under an open source license can prevent them from becoming discontinued as maintenance can be uptaken by others. However, this is more or less a theoretical feature as most systems are not getting a maintenance community.

Model coupling A key challenge with DSS-WuK has been the development of an integration concept for different data sources and models - a general challenge in the development of Environmental Information Systems due to their interdisciplinarity [e.g., Sanchez-Marre et al., 2008, Liu et al., 2010, Schmehl et al., 2010]. A promising approach was developed with the DSS-WuK mastermodel using a point-based modeling concept and a data exchange interval between the submodels. Furthermore, the DSS-WuK mastermodel was based on the reuse and coupling of different existing and partly extended submodels. By coupling the different submodels a holistic assessment became possible incorporating several biotic and abiotic disturbers as well as an economic assessment. Such a holistically risk assessment is still rather rare although highly required as recently reported by Newman et al. [2017] and Orazio et al. [2017]. However, it is well known that as more realistic the models are the more complex the systems become at the same time, what can overwhelm users as reported by, e.g., Vacik and Lexer [2014]. Therefore, finding a balance between complexity and ease of use is crucial but difficult, as reported by Reynolds [2005] as well as Trasobares et al. [2014]. Nobre et al. [2016] concluded that academia tends to make systems too complex, which applies partly to DSS-WuK and BEAST as well. However, Skyrius et al. [2013] suggested to build two tier systems with (1) a simple, fast and often used component and (2) a detailed and less often used part. This approach is applied in DSS-WuK by providing (1) the fast and rough overview maps and preprocessed system on the one hand and (2) the detailed, request-specific dynamic simulation component on the other hand. Also in BEAST this systematic is implemented by providing optional functions for more detailed, processing-intensive analysis.

In contrast to this systematic, Vacik and Lexer [2014] as well as Rammer et al. [2014] recommended a toolbox approach for the development of DSS with various simple and modular tools instead of highly integrated monoliths. Such a toolbox approach would prevent interactions between the submodels but the implementation would be much faster, feedback by users would be gained earlier, complex interfaces for coordination between submodels would be unnecessary and extension and communication of the systems' functioning would be much easier. From the experiences of DSS-WuK it seems that forestry practitioners seem not to be ready for complex coupled models to assess the impacts of climate change by themselves with DSS techniques.

In retrospect, to create a marketable product, a toolbox approach seems to be more

promising. However, an important result of the development of DSS-WuK is the identification of research/knowledge gaps at the interfaces between the different submodels, which become obvious only when deep integration of submodels is tried - an output of DSS development already mentioned by Cox [1996]. With DSS-WuK it became obvious for all ecological models that large gaps of scientific knowledge exist when it came to transformation calculation of disturbance exposure to damage. For example, the calculation of wind speeds and the resulting wind pressure to the trees was a complex model calculation but physically good describable. However, deriving the amount of damaged timber in a forest stand from this wind pressure has not yet been investigated adequately. Furthermore, the submodels have not been developed originally to be integrated to a holistic risk assessment system what made the development of the interfaces difficult. Nevertheless, only studies such as DSS-WuK are able to deeply uncover such knowledge gaps based on existing scientific results. However, as the intention of DSS-WuK was to create a tool for practical application this result had a lower priority compared to ease of use and user acceptance and cannot be compensated by good visualizations as stated by Vacik and Lexer [2014]. Therefore, the recommendation for similar projects is that the systems should start with simple modular tools and should only increase complexity on the long run to enable users to gradually increase their knowledge and believe in the system. However, this requires that funds are available to start with making existing simple tools available for practical use as well as funds are available for long term development - which is often not the case. It should be clear, if the knowledge transfer from science to practical application is in focus or, alternatively, the development of an integrated system. With one system both would mostly not be reachable at the same time.

Model and data reuse, quality, and availability The reuse of existing models and data for the development of a DSS, as done for DSS-WuK, is still a promising approach, also recommended by Packalen et al. [2013]. Not only on a conceptual level but also on a technical level, DSS-WuK presented a promising approach for coupling existing simulation models implemented in different programming languages/environments on an API level with object-state memory without making use of error-prone file exchange with read-/write-operations. A further alternative would have been the encapsulation of models with web-services [cf. Usländer, 2010]. This opens the opportunity to connect models running on different machines and written in different programming languages through well-defined interfaces. At the time of development of DSS-WuK state storage, as possible in object-oriented programming, was not sufficiently supported in web-service based design and network bandwidth was a potential bottleneck. Nowadays, the (web-) service-oriented architecture (SOA) is a common approach to orchestrate different software artifacts in business applications [cf. Romero and Vernadat, 2016]. Nevertheless, web-service based designs seems to have not the same popularity in natural resource modeling. The use of well-defined XML web-services enables to automatically generate interfaces and input forms by self-description as well as to integrate the same services into different platforms. When following the toolbox approach, providing the models with web-service interfaces is a good starting point to couple the models later by providing an additional orchestration component equivalent to the DSS-WuK mastermodel. Service-oriented architectures increase the flexibility, the adaption performance to changing requirements and the reuse options [cf. Zhang, 2010].

Nevertheless, reuse of models for building EnvIS is still seldom, inter alia due to closed

codes, weak documentations and/or unclear licenses [cf. Holzworth et al., 2015]. DSS-WuK and BEAST have been provided under the GNU GPL open source license - however, license situation for reused submodels in DSS-WuK prevented their distribution. This situation should be improved in general. In spatial data area the situation already changed by the establishment of open standards. The provision of Web Mapping Services (WMS), Web Feature Services (WFS) as well as Catalogue Services for the Web (CSW) are widely distributed and also used with DSS-WuK and the presented eResearch Infrastructure. Web-processing services, instead, are still not that common but have the potential to modernize the spatial Decision Support System development, provision, and reuse.

The availability and quality of data, models and knowledge are often problematic for Environmental Information Systems, as reported by Segura et al. [2014], Papathanasiou and Kenward [2014], Kempenaar et al. [2016], and Wolfert et al. [2017]. For DSS-WuK the availability and quality of climate change scenario data were an issue. Only CLM data were available for the project and the quality was rather low. Up-to-date ensemble simulations were not available at the time of development and funds for buying further data were not approved. This experience results in the recommendation to consider carefully the availability of required data, models, and knowledge already at time of grant application/project planning. The availability of data was also a restriction for the development and usage of BEAST. In contrast to DSS-WuK, BEAST did not integrate various process-based and statistical models. Instead it provided a Multi-Criteria Decision Analysis (MCDA) based on preprocessed data and, therefore, externalized complex model simulations into the input data generation process. The data model was designed to be able to incorporate also climate change effects but the data needed to be provided by the user. This made the system very flexible for the application to different study areas as well as for the usage with different growth models, however, this required the provision of adequate data. Thus, the application of the system in group decision processes needed elaborate preparations and hampered its uptake in practice. Therefore, the system was applied only for academic studies so far and not for practical applications in regional bioenergy plannings, although the approach is under evaluation by the International Energy Agency (IEA) for recommendation [Busch, 2017].

The data availability could be improved, if a culture of open data provision and sharing would be established. The lack of such a culture not only hampers the development and usage of DSS but also the usage of data management and harvesting systems, i.e., (spatial) data repositories and infrastructures, as well as EnvIS in general. Furthermore, such a culture is required to improve reliability and reproducibility of scientific findings as described, for example, by Pfaff et al. [2015]. The technical solutions and standards are already available, as presented in this thesis as well as by others [e.g., Steiniger and Hunter, 2012]. However, it is inefficient to implement individual systems for each project. Instead, with an increased culture and request of such systems, it is more efficient to create central services provided, for example, by scientific libraries. At the time of the DSS-WuK and the BEAST projects such services were not available at the local campus. In the meantime, such services have been developed at the Göttingen Campus [Dierkes and Schmidt, 2015, Dierkes and Wuttke, 2016] as well as at several other research institutions [e.g., Richardson et al., 2012].

Desktop and web-based application The eResearch Infrastructure for collaboration and data management was implemented as a web-based system, i.e., accessible via a web-

browser through the Internet. This is necessary for those systems as they must be available independent from time and space. The demand for those systems increases by the fact that developing system solutions for the large environmental challenges, such as land-use and climate change, require interdisciplinary research and collaboration.

The DSS-WuK was also implemented as a web-based system due to the large amount of climate data in conjunction with restricted usage and distribution rights. Therefore, the data needed to be stored and used on the backend server and were not allowed to be supplied through the system. Therefore, a downloadable software with packaged climate data could not be distributed. The web-based system has several further advantages as described, for example, by Shim et al. [2002], Murphy [2003], Bhargava et al. [2007], and Rossi et al. [2010]: an increase of accessibility including independence from a specific platform and the possibility of mobile use, the potentially wide audience and the central maintenance. However, this is not generalizable. Oliver et al. [2017], for example, found that mobile access was not requested by stakeholders for a system supporting on-farm microbial risk assessment.

In contrast to DSS-WuK and the general trend to develop web-based systems, the BEAST system was implemented as a local (Desktop) software as it came without a large amount of data. The system needed to be applicable in group decision panels where access to the Internet could be restricted and the input data may not being exchanged via the Internet. Users feel more secure when their data and scenario results are not transferred through the Internet and are kept on the local machine in their own hands. As the system was written in the Java programming language it is also platform-independent and with some adaptations executable on mobile devices as well.

Stakeholder involvement and user uptake Stakeholder involvement in system development has been of great importance for DSS-WuK. The system has been developed evolutionary with several feedback panels with stakeholders and potential users, a process also called evolutionary prototyping [see D’Erchia et al., 2001]. General aspects of climate change impact were discussed with stakeholders and system application was tested and discussed with users. The involvement of stakeholders is seen as a key success factor of DSS and is often missing [see, e.g., Salewicz and Nakayama, 2004, McIntosh et al., 2011, Pastorella et al., 2015, Newman et al., 2017, Oliver et al., 2017]. The involvement ensures that the system is problem-oriented and useful, easy to use, credible, transparent, and promoted by stakeholders. Although, such an involvement and evolutionary development is an elaborated process, it strongly helps to bridge the transfer gap from science to practice and increases the practical relevance of any Environmental Information System. As described by Lejeune et al. [2010] and Zasada et al. [2017], the identification of relevant stakeholders and the right time of involvement is difficult. With DSS-WuK, for example, stakeholder selection was strongly influenced by personal connections of the project team members and did not represent the whole set of stakeholders. At the same time, the set of selected stakeholders in the DSS-WuK project was too heterogeneous resulting in excessive expectations. For example, representatives from nature conservation organizations asked for completely different functionality comparing to forest owners. Due to complexity as well as lack of data and models the project was not able to meet all expectations. Therefore, in future projects the target group and the expectations should be better clarified at the beginning. The relevant stakeholders should be selected more suitable regarding the target. Poch et al. [2017] re-

ported that DSS development driven by academia instead of stakeholders could be better on the long run due to a wider perspective. This may be true theoretically but systems not accepted by users will not be used in practice and cannot act as linkage vehicle between academia and practice - the key role of DSS developed in scientific projects.

A specific problem of user acceptance in German forestry sector results from the federal structure of forest administrations and corresponding research institutes. Especially in forest growth modeling and climate change impact assessment all forest research institutes have their own separated approaches. It seems that there is no genuine interest in the approaches of the others to protect its own reason of existence. A system applicable to whole Germany is not in the interest of those federal organizations and, therefore, will always have problems in stakeholder and user acceptance. The greatest interest and acceptance of DSS-WuK came from users and organization from Northern Germany, as they were well represented in the stakeholder group and project team. In summary, this underpinned the relevance of stakeholder involvement as a success factor and marketing effect for DSS.

V.2. Outlook

As shown in this thesis the research field of Environmental Information Systems is manifold. The focus here was on decision support, collaboration, and data management systems.

The demand for such systems will further increase in the future as the amount of data and information will increase due to the on-going digitization. New data generation as well as processing technologies will increase the data creation rate. However, data quality and availability will still be a challenge.

Environmental challenges, such as pollution, climate and land-use change, in conjunction with societal changes will result in a stronger request for transparent, adaptive, and participatory decision making. Therefore, further research on and development of Environmental Information Systems will be needed. Especially the fact that despite several decades of research many systems still do not accomplish the transition from academia to practical application will be a major task. Several authors already defined success factors of Information Systems, however, evidence of the assumptions have not been provided. It is easier to prove why a system failed instead of describing why a system is successful. More research is needed to describe the success factors of Environmental Information Systems in different application circumstances. Although, this thesis dealt mainly with computational/technical aspects of Environmental Information Systems organization, processes and persons must also be taken into account for the success of such systems. Ten years after the beginning of the development of DSS-WuK there is not much progress in strategies how to bring EnvDSS developed in academia to practical relevance. It seems, it is time for new approaches - some has been discussed in the lessons learned - however further research is required.

Furthermore, frameworks for the combined application of computerized and non-computerized systems in group decision processes are needed. Systems like BEAST must be integrated into larger frameworks for structuring group decision processes. Here, further research and best practice examples for such integrations are needed, especially in regional bioenergy plannings.

Expectations concerning Environmental Information Systems and especially Decision Support Systems need to be kept realistic. There are areas where Artificial Intelligence can replace humans, however, currently, DSS are tailored to assist humans in making decisions not to replace the human decision maker. Therefore, the responsibility for decisions is still in the

hands of human decision makers and the application of a DSS does not automatically result in better decisions. Instead, often functioning and results of DSS are not well understood by decision makers what is resulting in misleading result interpretations. Here, better ways to communicate functioning and results are needed. This thesis presents examples, but more best practice examples with stakeholder feedback should be conducted.

The development of case studies as best practice examples are useful for developing and testing different scientific approaches, for practical acceptance testing, and as starting points for further studies. Also failed studies and their lessons learned are useful to make Information System development more efficient. However, more comparative studies of different approaches are needed. This requires the willingness for comparisons by all system developers, which is currently not always given.

As shown with DSS-WuK, further research is needed to develop robust models for the transition of hazards into quantitative impact measures. Moreover, the interactions/feedbacks between different biotic and abiotic disturbers are not well quantifiable, currently.

Furthermore, interoperability of models and data is often not ensured, what hampers or prohibits their reuse. Efficient progress in science is based on reusing the findings of others and deriving new results on top of this existent knowledge. The establishment and usage of interoperability standards can foster this. It needs appropriate circumstances including the willingness of producers to provide their data and models and the users to built upon this available products. Open source licensing can help to clarify the legal framework. It needs a new culture of exchange with incentives, pressure, and established services. A rethinking at funding organizations has already began. They increasingly request for professional data management and publishing at large scale projects. This process need to be continued. Preparing data for publishing as open data as well as creation of the corresponding metadata is a time consuming task [see, e.g., Pfaff et al., 2015]. At the same time the value and reputation of data publishing for the individual researcher must be increased to strengthen the willingness of data provision. At the end, results produced with public money should be given back to the public. Environmental Information Systems can be target of exchange themselves on the one hand and can support the exchange of information on the other hand.

V.3. References

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Figure A.1.: Start page of Digital Supplements.

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