UNIVERSITY OF NOVA GORICA
GRADUATE SCHOOL
STUDY PROGRAMME: ENVIRONMENTAL SCIENCES

EMERGY ANALYSIS OF BLACK ALDER (*Alnus glutinosa* (L.) Gaertn.) FLOODPLAIN FOREST GROWTH

Jana LAGANIS

Dissertation

Mentor: doc. dr. Marko Debeljak

Nova Gorica, May 2007

ZAHVALA

Pestra, polna mavričnih trenutkov je pot življenja. Mirna ravninska stezica se včasih že naslednji hip strmo dviga ali prebija skozi navidez neprehodne goščave, znova in znova obstane na razpotjih… A k sreči nas na njej spremlja veliko prijaznih src, ki podajo roko in prisluhnejo ritmu naših korakov.

Šele ob pogledu nazaj sem dojela množico vseh, ki ste me spremljali skozi križišča, ovinke in zaplete, vse do teh vrstic. Pokazali pot, me pospremili, pripomogli s prepotrebnimi nasveti in znanji, znova in znova prisluhnili mojim popotnim razmišljanjem in obogatili potovanje s svojimi doživetji in izkušnjami.

Hvala vam, soborci v sosednjih pisarnah in pri sosednji mizi. Za zgled poguma in vztrajnosti na poteh preko tankega ledu in ob prebijanju skozi zamete. Za izjemno odprtost in sprejemanje v trenutkih, ko se je zdelo, da je vse zamrznilo. Za vse pogovore, nasvete, drobne dogodivščine...

Iskrene zahvale Tomu in njegovi ekipi, gozdarjem v Lendavi, Ljupču, Aleksandru in ostalim pod Saševo taktirko, sončno obarvani emergijski in solinarski četici, Klari, Metki, Tjaši, Andreji in množici ostalih, ki ste mi pomagali prenesti sto in eno breme, dopolnjevali energijske in emergijske zaloge, opozarjali na razglede in stotine vprašajev spreminjali v klicaje.

Posebna zahvala tebi, Marko. Za utiranje prvih korakov skozi goščavo neznank, za nasvete in usmerjanje v križiščih in za spremstvo na vijugah te poti. Za opominjanje in opogumljanje, za iskreno kritiko in prav tako iskreno pohvalo.

Srčne zahvale vam, ki ste z menoj prenašali življenjsko prepletanje te poti, mi stali ob strani in z zaupanjem spremljali vse, tudi najbolj klecave korake. Boštjanu, prijateljem, obema družinicama Laganis. Vama, starša. Za smerokaze, ki so trmasto kazali vedno v isto smer, in za preplet podpore, svobode in odgovornosti, ki ga vedno znova občudujem. Za opominjanje na barvitost mavrice in vabečo svetlobo sonca nad oblaki.

In končno najbolj sanjave zahvale tebi, Peter. Za dlan, ki potuje prepletena z mojo dlanjo, in za ramo, ki pričaka utrujeno glavo. Za skupne sanje, za neomajno potrpežljivost in podporo, za smeh in iskrenje. Da si…

Čisto na koncu ne morem mimo izraza občudovanja Življenjski sili. Na pot je postavljala izzive, ob njej zbujala polja cvetov, pospremila dneve s ptičjim petjem in s krili metuljev, risala sončne vzhode in zahode… In gnala naprej in naprej.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

ABBREVIATIONS AND SYMBOLS

avergw: Average level of groundwater in the given period (the data for a well in Gornji Lakoš).
averL: Average Ledava River level in the given period (the data for the Čentiba measuring station).
averT: Average measured temperature in the given period (the data for Lendava).
cumT>0: Cumulative temperature above 0ºC in the given period (the data for Lendava).
cumT>10: Cumulative temperature above 10ºC in the given period (the data for Lendava).
cumT>5: Cumulative temperature above 5ºC in the given period (the data for Lendava).
DBH: Diameter at Breast Height, diameter of a tree measured at 1,3 m of height.
EIR: Emergy Investment Ratio (EIR = (M+S)/(R+N) (see Chapter 3.3.4.6).
ELR: Emergy Loading Ratio (ELR = (N+M+S)/R)) (see Chapter 3.3.4.6).
ET: Evapotranspiration.
ET_a: Actual evapotranspiration, evapotranspiration that actually occured.
ET_o: Reference (or potential) evapotranspiration, evapotranspiration from reference surface, not short of water.
ET_{oa}: Adapted reference evapotranspiration; reference evapotranspiration that was lowered during drought periods.
EYR: Emergy Yield Ratio (EYR = Y/(M+S))) (see Chapter 3.3.4.6).
GPP: Gross Primary Productivity.
LAI: Leaf Area Index; one-sided leaf area per unit ground area (m^2/m^2).
MAE: Mean Absolute Error; the average of the difference between predicted and actual value in all test cases; it is the average prediction error.
maxgw: Maximum level of groundwater in the given period (the data for the well in Gornji Lakoš).
maxL: Maximum Ledava River level in the given period (the data for Čentiba measuring station).
maxT: Maximum measured temperature in the given period (the data for Lendava).
mingw: Minimum level of groundwater in the given period (the data for the well in Gornji Lakoš).
minL: Minimum Ledava River level in the given period (the data for Čentiba measuring station).
minT: Minimum measured temperature in the given period (the data for Lendava).
MSE: Mean Square Error; the average of the squared differences between each computed value and its corresponding correct value. It is one of the most commonly used measures of success for numeric prediction (see Table 6).
NPP: Net Primary Productivity.
RAE: Relative Absolute Error; the total absolute error made relative to what the error would be if the prediction simply had been the average of the actual values.
RMSE: Root Mean Square Error; the square root of the mean-squared-error. The RMSE gives the error value the same dimensionality as the actual and predicted values (see Table 6).
RRSE: Root Relative Squared Error; the square root of the RSE is taken to give it the same dimensions as the predicted values themselves (see Table 6).
RSE: Relative Squared Error; the total squared error made relative to what the error would be if the prediction had been the average of the absolute value (see Table 6).
SLA: Specific Leaf Area (kg/m^2) (see Chapter 3.1.1.1).
T_{corr}: Correlation coefficient (see Table 6).
thinn: Volume of removed wood before the current growing season (m^3).
thinn y-1: Volume of removed wood before the previous growing season (m^3).
thinn y-2: Volume of removed wood two years before the current growing season (m^3).
tsun: Duration of sun radiation in the given period (the data for Lendava; hours).
UEV: Unit Emergy Value; amount of emergy per unit of weight, energy, or information. Previously the term trasformity was used.
%R: Renewable Emergy Fraction (%R = R/(R+N+M+S) = R/Y = 1/(1+ELR)).

1 INTRODUCTION

1.1 Introduction to the research problem

Environmental systems were recognized to be extremely complex systems, which cannot be fully understood. Nowadays we try to organize and test our knowledge on ecosystems through ecological models. The quality of models is mainly dependent on the quality of our knowledge and on the data about the environment. One of the most critical questions in the modeling is which variables are crucial and which can be neglected. The goal is to construct models with as many ecological properties as possible and to test them from the ecological point of view (Jørgensen, 2002).

In parallel with increased awareness of the exceptional complexity of the natural system, new approaches for their research have emerged. Holistic Ecology (Doherty and Rydberg, 2002) treats ecosystems as inseparable wholes. One possibility to do this is to study thermodynamic properties of ecosystems, which is the major tool of Systems Ecology methods. These methods are able to provide information about the health and sustainability of ecosystems under study (Jørgensen, 1999 and 2002).

Emergy synthesis is one of the methods developed to evaluate ecosystem processes and their properties. It is a relatively young and promising environmental accounting approach based on open system thermodynamics. One of its major advantages is the ability to evaluate systems that are driven by multiple forms of energies (Tilley, 1999), by expressing all flows in one common unit, in general solar equivalent energy (also “solar emergy”). Solar emergy, a measure of the total environmental support driving a system, is a scientific measure of a system’s sustainability based on the analysis of the quality as well as the renewability of supporting flows and their availability in the long run. It could be defined as “a scientific measure of real wealth in terms of energy required to do work or production” (Odum, 1996). It enables us to compare contributions of individual emergy flows to the final product. Flows with the highest emergy contribution are expected to have the greatest impact on ecosystem function and structure.

Ecological systems are very dynamic systems (Jørgensen, 1999). According to the pulsing paradigm (Odum, 1983, 1995b and 1996; Odum and Odum, 2006) there is no constancy in the nature and each existing ecosystem is just a moment in the long-term cycle of oscillations. The rules controlling and directing their function are mainly unknown or poorly known. Their structure and function undergo several changes during development phases and as a response to changes in the environment. Many of nowadays changes in the environment are caused by human activities and when the loading exceeds a critical value or frequency it can present a threat to ecosystems. On the other hand, we must keep in mind basic ecosystem properties: its adaptability, changeability, uniqueness, and indeterminability. They disable reliable prediction and determination of consecutive changes in ecosystems. In many cases it is not easy to clearly distinguish between natural fluctuations and human-induced changes, as their effects are interlaced.

The study of different ecosystems has proved that some of their properties can be regarded as indicators of their functions. In this way annual radial increments of individual trees in temperate forests are regarded as records on production intensities in individual years. In forests that would be out of human impact, annual increments would depend solely on resource availability, hydrology and climate conditions. In ecosystems under human impact there are other factors like management-induced changes and loading, which can be of same or even greater importance. Will it be possible to find an appropriate tool to identify attributes that most importantly affect radial increments and consequently the function of the selected ecosystem?

The focus of the present research was the link between oscillations in invested emergy and annual increments, as indicators of ecosystem function. Was there an interdependence between the magnitude of emergy (in)flows and annual production in individual years? Have the environmental attributes with the highest emergy contributions caused the most important changes in the environmental function? Were environmental and management emergy flows of the same importance? Was the system development in agreement with the Maximum Empower Principle (Odum 1995a; Odum and Odum, 2001a, p.70 and 2006; Campbell, 2003a)? Is it possible to bring forest management closer to this principle?

1.2 Review of literature

This chapter reviews literature and introduces the three major topics that were included in the research: emergy synthesis, ecological properties of black alder, and ecological modeling.

The first part of the literature review discusses basic principles, problems, and hot topics in emergy synthesis which was in the major focus of the research. Previous emergy syntheses on forest systems and previous studies, which introduced dynamics into emergy synthesis, are reviewed. The second part reviews the existing knowledge on physiology of black alder trees and properties of alder floodplain forests that are important for this research and for the modeling. The third part overviews basic purposes and types of ecological models, their properties, their advantages and limitations.

1.2.1 Emergy Synthesis

Emergy Synthesis arose from the General System Theory, irreversible thermodynamics and Ecology, which together formed the basis for the Energy Systems Theory (Odum, 1996; Brown et al., 2000; Campbell, 2004). It is based on the Maximum Empower Principle, which is regarded as a general criterion for judging the impacts of human activities on the planet (Cohen et al., 2005; Franz and Campbell, 2005). This principle has been mathematically formulated (Giannantoni, 2000, 2002,d 2003).

According to the Maximum Empower Principle (Odum, 1996 and 2002; Odum and Odum, 2001a and 2006, p.70), self-organizing systems develop organizations that maximize use of emergy that is received by the system and that minimize loses. Through optimization of efficiencies and feedback reinforcements systems achieve maximum useful (em)power on every scale (Brown et al., 2000; Odum, 2000a; Ulgiati, 2000; Campbell, 2003a). The selective pressure tends to isolate and remove components that fail to provide commensurate services. Consequently changes are a consistent ecosystem property, as it is predicted in Pulsing Paradigm (Odum, 1983 and 2003).

Emergy synthesis compares environmental, economic and social values on a common counting base – the solar energy it took to make them. In contrast to economic analyses it can determine purchased and non-purchased resources, services and commodities (Odum et al., 2000a). Consequently it is able to overcome diversity of metrics used for quantifying processes and activities (Tilley and Swank, 2003). The view that the systems are all connected through flows of emergy is one of the most important advantages of emergy language (Patten, 1993).

Emergy Synthesis approach was developed by H.T. Odum and it is extensively explained in the book Environmental Accounting (1996), in published articles (Brown and Ulgiati, 1999; Odum, 1988, 1998, 2000b and 2002 Brown et al., 2000; Ulgiati, 2000; Hau and Bakshi, 2004) as well as in Folios published by Center For Environmental Policy, University of Florida (www.emergysystems.org). Emergy is a method of valuation that is based on the total amount of energy of one kind used directly or indirectly to make a product or service (Odum and Odum, 2001a,b). In this way it can be considered also as “energy memory” as it accounts for all energy that was invested into production of a product or service (Odum, 1996). The solar emergy is used as a common “currency” for the analysis of industrial and ecological systems (Bakshi, 2002). Consequently it can be used to estimate the loading (excess demand) on the environment that is caused by a production process. It can be used to compare the sustainability of different production processes alternatives. Different energy qualities are compared through the introduction of transformation coefficients, so called Unit Emergy Values (UEVs).

1.2.1.1 Problems and actual topics in emergy synthesis

Notwithstanding its advantages (Patten, 1993; Odum, 1995a; Hau and Bakshi, 2004) emergy has undergone many critics (e.g. Månsson and McGlade, 1993; Cleveland et al., 2000). Many of these criticisms are common also to other methods for joint analysis of industrial and environmental systems. Criticized were also its bookkeeping procedures and thermodynamic assumptions (Ulgiati, 2000). Economists marked it as an “ecocentric” approach. The majority of people have problems when accepting the fact that environmental services and sources are not for free. Moreover, they often misunderstand emergy concept and indices (Odum, 1983 and 1995a; Hau and Bakshi, 2004; Raguei et al., 2005; Ulgiati et al., 2005). Many critiques are common also to other techniques dealing with both environmental and industrial system (Hau and Bakshi, 2004; Vieira et al., 2005).

Referring to Doherty and Rydberg (2002) and Hau and Bakshi (2004) among the most criticized elements and handlings of emergy synthesis are:

- Chosen one-dimension measure of emergy excludes or deals only indirectly with other aspects like different properties of chemical and social aspects.
- Dependence on the tables of Unit Emergy Values (UEVs) calculated in previous researches. These criticisms pertain to uncertainty, sensitivity, quantification, and use of inappropriate UEVs.

The future success of Emergy Synthesis seems to be mostly dependent on developing accurate and consistent methods for calculating UEVs (Campbell, 2000). In many cases it would be needed to perform sensitivity or uncertainty analysis. Fortunately the method was found to be robust to the extent that different approaches to calculation of UEVs may give approximately the same results (Collins, 2003). Several methods are used to calculate UEVs nowadays (Brown, 2005) including static calculation, dynamic calculation (e.g. Tilley, 1999; Bardi, 2002; Cohen, 2003; Collins, 2003; Tilley and Brown, 2006), and network analysis (Collins and Odum, 2000; Collins 2003; Bardi et al., 2005; Brown, 2005).

Among more "technical" problems encountered in emergy synthesis Campbell et al. (2005) note:

- choice of applied planetary baseline (Odum and Brown, 2000; Campbell, 2003b);
- problems in identifying splits and coproducts to avoid double counting (Bastianoni and Marchettini, 2000; Tilley and Brown, 2006);
- difference between received and absorbed emergy (Brown and Bardi, 2001).

Hot topics in emergy synthesis cover many different fields:

- pollution and emissions (Bastianoni, 1998; Buranakarn, 1998; Bakshi, 2002; Ulgiati and Brown, 2002; Brown, 2003; Yang et al., 2003; Vieira et al., 2005);
- applications of emergy to sustainability evaluation (Federici et al., 2003; Vieira et al., 2005; Castellini et al., 2006);
- information (Keitt, 1991; Tilley, 1999; Jørgensen et al., 2004) and biodiversity (Keitt, 1991; Tilley, 1999; Tilley and Swank, 2003; Cohen et al., 2005; Franz and Campbell, 2005);
- landscapes and their changeability (Bardi, 2002; Kangas, 2002; Martin, 2002);
- nations, economy and monetary values (Campbell, 2001; Cleveland et al., 2000; Huang and Hsu, 2003; Campbell et al., 2004; Vieira et al., 2005);
- comparisons of emergy to other systems ecology approaches (Jørgensen et al., 1995 and 1998; Patten, 1995; Bastianoni and Marchettini, 1997; Bastianoni, 1998; Pereira and Nebra, 2000; Tilley, 2003; Herendeen, 2004); and
- integration of emergy and other thermodynamic-based approaches and with modeling in order to develop promising new techniques (Ulgiati, 2000; Hau and Bakshi, 2004; Bakshi, 2002; Brandt-Williams and Lagerberg Fogelberg, 2005).

1.2.1.2 Emergy synthesis of forest ecosystems

Emergy synthesis is frequently used to quantify the structure and performance of environmental systems to aid in environmental decision-making (Tilley and Swank, 2003). Several emergy studies were performed also on forests, agro-forestry systems, and floodplain forest ecosystems (Tilley, 1999; Bardi and Brown, 2000; Bardi, 2002; Scatena et al., 2002; Lefroy and Rydberg, 2003; Tilley and Swank, 2003). It was shown that emergy synthesis could offer valuable insight into the consequences of meeting the public's increasing diversity of goals for natural resource use. It can also aid in determining forest policies that are ecologically, socially and economically sustainable (Tilley and Swank, 2003).

It is known that if more work is left to nature, higher net emergy is gained from the forest, but the time required is longer (Odum, 1996). Emergy accumulation and the quotient between invested emergy and stored energy (Unit Emergy Value; UEV), in other words, the quality of ecosystems work, is not only a function of the energy of storages, but also of the time it takes to accumulate value. Tilley's simulation (1999) showed that the amount of energy, emergy and the UEV of biomass all increased in time in a forested ecosystem. The physical components (energy storages) reached their maximum value at a faster rate than both emergy and UEV. On the opposite the results of research of Bardi (2002) showed that UEV of biomass had higher initial than steady state values.

Wetland ecosystems were found to contribute on average more wealth (environmental services) to society than upland ecosystems. They contribute almost six times the environmental services of upland ecosystems (Bardi, 2002), which reflects the importance of wetland ecosystems.

In contrast to the majority of emergy evaluations that were done in a static way, a dynamic approach was introduced relatively early in emergy syntheseis of forest ecosystems (Tilley, 1999; Bardi, 2002; Tilley and Swank, 2003; Tilley and Brown, 2006). This could be explained by the fact that dynamic approaches are especially important in calculating UEVs of resources that require longer time to generate and for systems that do not operate in continuous and well-established way (Brown, 2005).

1.2.2 Ecological modeling and forested ecosystems

The universe in which we live is far too complex for the human mind to understand and visualize in detail all at once (Odum and Odum, 1999) and we will never be able to give a complete and comprehensive description of the world (Jørgensen, 2002). In ecological modeling we try to synthesize our knowledge to describe the relationships among members of living communities and their abiotic environment (Džeroski, 2002). Therefore the quality of the model is very dependent on the quality of our knowledge and the available data (Jørgensen, 2002). Models can be used to better understand the domain at hand or to predict the behavior of the studied communities and thus to support decision making for environmental management (Odum and Odum, 1999; Džeroski, 2002). In ecological modeling care must be taken to keep the complexity of generated models within reasonable limits (Jørgensen, 2002).

In typical ecological modeling approach an expert writes down a set of differential equations that capture the most important relationships in the domain. The coefficients of these equations are then calibrated using the measured data. In ecological modeling linear equations are often applied, whereas relationships between living communities are usually highly nonlinear (Džeroski, 2002). Dynamic approach is more proper in presenting dynamic reality. The importance of dynamic applicators was stressed by many authors (Odum, 1996 and 2003a; Tilley, 1999; Bardi, 2002). However, in each modeling approach we must be aware that whereas reality operates "in" time, in real time, dynamic modeling operates "on" time, serving to compress it in such a way that it provides us with a view of the evolution of our constructions through time.

In some cases models were considered dynamic as soon as the simulation showed the temporal patterns (Odum, 2003a) or when the method of analysis included evaluation of trends (Vieira et al., 2005). On the contrary, the majority of models in environmental science, which can be regarded as dynamic, use differential or difference equations to describe the systems response to external factors (Jørgensen, 2002). Recently the next generation of ecological models is appearing. These, so-called structural dynamic models, are able to capture structural changes after a change in driving attributes, what is usually named adaptation (Jørgensen and DeBernardi, 1998; Jørgensen, 1999). However, due to their high complexity and resulting uncertainty Jørgensen (1999) still advices that we use ecological models as far as possible.

In ecological modeling we usually use computer simulation programs. These are sets of logical steps in sequence, which together represent a system process (Odum and Odum, 1999) and they enable the researcher to get a new knowledge about many interacting processes and about the entire system (Jørgensen, 2002). Observations and insights are used to develop new ideas for further development of the model. Three the most significant steps in modeling procedure are calibration, verification and validation. During the calibration we estimate model attributes. Verification is used to test, whether the model reacts as it was expected and if it is stable in the long run. Validation includes sensitivity analyses (Jørgensen, 2002) and tests on new examples.

Several different graphical programming languages are available that are specifically designed to facilitate modeling of nonlinear, dynamic systems (e.g. EXTEND, FORTRAN, MATLAB, ECOSIM, SIMUL8). Among the most versatile of these languages is the graphical programming language STELLA®. STELLA is an icon-based, object-oriented graphical programming language, designed specifically for modeling dynamic systems (Costanza, 1998) and for process optimization. It was one of the first dynamic modeling systems to achieve broad recognition and use, in large part due to its user-friendly graphic interface (Costanza and Voinov, 2001). Results of former studies that showed its appropriateness for systems analyses (Pan and Raynal, 1995; Costanza et al., 1998; Woodwell, 1998;

Jørgensen, 1999; Costanza and Voinov, 2001), as well as clearness and accessibility were the promising signs, which showed that it would be possible to use STELLA for our purposes. STELLA was already used in out previous work on emergy synthesis of saltpans of Sečovlje (Laganis and Debeljak, 2006), based on emergy synthesis of this traditional salt production process (Babič, 2005).

Several different modeling tools have been developed for forest growth simulations (e.g. JABOWA, ORGANON, Stand Visualisation System, Forest Vegetation Simulator, SimForest, SILVA, TREEDYN3, etc.). However, no one of them was appropriate for coupling with emergy synthesis and just some of them were able to simulate growth of an alder stand.

1.2.2.1 Dynamic emergy approaches and their advantages for emergy synthesis

Dynamic simulation programs were developed to enable time-dependent simulation of ecosystems. The possibilities to apply modeling in emergy accounting were recognized early after emergy conceptualization (Odum, 1995 and 1996). This could be explained by the similarity of logic in ecological modeling and in emergy evaluation (see Chapter 3.3.2).

The first steps toward dynamic simulations of emergy flows and indices were intended to test the theory and theoretical knowledge (Doherty, 1995; Odum and Peterson, 1996; Odum and Odum, 2000; Odum 1996, 2000a and 2003; Collins, 2003). Some temporarily dynamic emergy accounting models were developed to test mathematical equations and to overview temporal dynamics for emergy flows and indices during the system development. The goal was also to test the importance of individual flows (e.g. Tilley, 1999; Bardi, 2002; Cohen, 2003; Collins, 2003; Tilley and Brown, 2006). These models were calibrated on the performed emergy analyses and on predicted or literature-based differential equations, sometimes also on the measured hydrological data (e.g. Tilley and Brown, 2006). Some examples are models on forest storages (Tilley, 1999; Bardi, 2002; Tilley and Brown, 2006), forest production (Doherty, 1995), emergy of tree diversity (Tilley, 1999), soil biomass (Bardi, 2002), and saprolite formation (Tilley, 1999).

Application of ecological models brings several advantages into emergy accounting:
- It enables fast and reliable emergy evaluations under different conditions and complexities (e.g. comparison of performance indicators of *End Use* to performance indicators *of a Source*; Ulgiati et al., 1995).
- They can include rules to continuously trace emergy flows in recycled material and in feedback flows (Buranakarn, 1998; Brown and Buranakarn, 2000).
- They enable consistent tracking of emergy in splits and coproducts and they enable “hybrid allocation methods” (Tilley and Brown, 2006), a promising method in problems regarding splits and coproducts.
- They offer an opportunity to trace the renewable fractions of purchased flows. This is especially important due to the relativity of the concept “renewable” (Brown and Ulgiati, 1999).
- They offer an opportunity to achieve more accomplished cradle-to-grave emergy evaluations of materials or flows (Ulgiati et al., 1995; Brown and Buranakarn, 2003).
- They improve overview on the calculation procedure, its complexity and particularities (e.g. social values, information, etc.)
- They can be used to facilitate learning of emergy and Systems Ecology.

1.2.3 Ecological properties of black alder

The floodplain forest of black alder (named also European alder or common alder) (*Alnus glutinosa* (L.) Gaertn.; fam. *Betulaceae*) in south-eastern Slovenia was selected as the most appropriate study site for our research. Why the common alder and why this stand?

Black alder was chosen due to the following advantageous properties:
- Its short lifetime and fast development (Johansson, 2000) enable attainability of the data on management, as well as hydro-meteorological data over a large part of the rotation period.
- It forms monospecific stands and consequently interspecies competition does not take place. Interspecies competition would make the model very complex and less reliable. Single species are also more sensitive to stress than functional properties of ecosystem (Jørgensen, 1999).
- Black alder forms even-aged stands. The age of the trees was known (2-year-old seedlings were planted).

- The initial density of planting and the intensity of thinning measures were known.
- This is the only plant species in Slovenia, for which clear-cutting is allowed due to unsuccessful internal regeneration (Forest Management Plans 1971-1980; Brus, 2005). The stand reached the end of its rotation period. Felling down enabled acquisition of stem disks for the dendrochronological analysis.

Common alder is a deciduous tree species with numerous special ecological properties and with high degree of adaptations to sites with high and standing groundwater (Gill, 1975; Levanič, 1993; Brus, 2005; Herbst et al., 1999; Johansson, 2000; Schrader et al., 2004) and with many properties of pioneer trees (Eschenbach and Kappen, 1999; Eschenbach, 2000). It grows throughout the whole Europe south of the latitude 60˚N (Johansson, 2000). It is restricted to moderate or extremely wet locations like peatlands and along streams (Eschenbach, 2000; Johansson, 2000; Baar et al., 2002). It has a high conservational as well as economical value (Teissier du Cros et al., 1984; Nemesszeghy, 1986; Vares et al., 2004). Large homogenous stands are very rare in Europe.

It is largely indifferent to the parent material of its soils (McVean 1953; Johansson, 2000). However, it does not prefer calcareous soils and is sometimes reported to be more successful on sandy and slightly acid soils (Seiler and McCormick, 1982). In Germany it grows mostly on the silicate parent material (Eschenbach, 2005).

It may survive up to 120 years on its best sites (McVean, 1953; Eschenbach, 2000), whereas heights of only 3-4 m and the ages up to 20-25 years were observed on poor ground (McVean, 1953).

Black alder's female catkins (Figure 1B) develop into cones-like structures (Figure 1C) that bear seeds. Seed production is typically 5-13 kg of seeds per hectare per year, but it can reach up to 18 kg/ha/y. In average there are 60 seeds per catkin (Funk, 1990). Alder seeds remain viable 2-3 years (Brus, 2005; Kotar, 2005) and their germination faculty is about 20% (Funk, 1990; Brus, 2005; Kotar, 2005). The aerage seed weight is about 0,004 g (Featherstone, 2003).

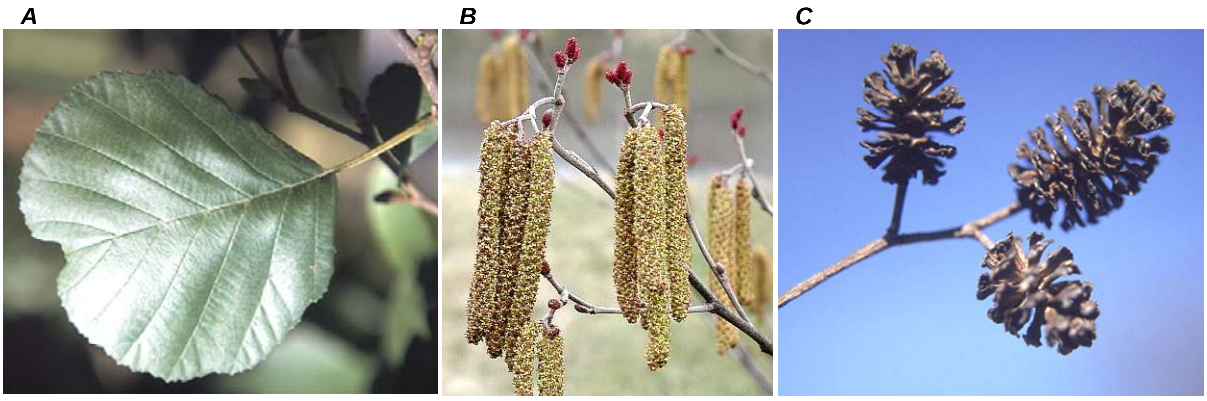


Figure 1 *Leaf (A), catkins (B), and cones-like structures (C) of black alder.*

1.2.3.1 Growing season

Growing season is defined as the period between leafing and yellowing in the autumn (Chmielewski et al., 2004). Changes that take place during the development of deciduous trees in this period importantly affect net primary production and annual growth (Baldocchi and Wilson, 2001; White et al., 1999). This is also the time when meteorological and hydrological conditions most importantly affect the primary production. The research of Baldocchi et al. (2005) and Baldocchi and Wilson (2001) showed that the length of carbon uptake period explained 80% of the spatial variation in the net annual carbon exchange of ecosystems across a latitudinal and continental gradient of deciduous forests. In the research of White et al. (1999) the change of one day' in the growing season length resulted in 1,6% change in NPP. The difference is larger in colder climates.

The beginning and the end of the vegetation period are dependent on species physiology and its frost resistance. For species with highly indeterminate growth, like black alder, early leafing was reported, as they risk only few leaves to late frost (Lechowitz, 1984). Also, early initiation and late cessation of the growing period were observed in black alder stands (Lechowitz, 1984; Giordano and Hibbs, 1993; Johansson, 1999; Vares et al., 2004).

The beginning of the growing season is believed to mostly depend on the temperature conditions in the late winter and in the spring (Eschenbach, 1995; Spano et al., 1999; Ahas, 2000; Middelhoff, 2000; Chmielewski and Rötzer, 2001; Rötzer et al., 2004; Brus, 2005; Črepinjšek and Bogataj; 2005). Chmielewski and Rötzer (2001) classified the region under study between natural regions 10 (Great Hungarian Lowlands/Danube-Save-Region) and 11 (Dinaric Mountain Region /Dalmatia). They note that the average starting-day of the growing season in this region is on 23rd April (day 113) and its ending-day on 28th October (day 301). Somewhat different data on average vegetation period in this region were reported for Slovenia (from 1st April to 30th September; Sušnik and Matajc, 2004) and for neighboring Podravlje, Croatia (from April to October; Antonić et al., 1998/99).

1.2.3.2 Growth properties and distribution of assimilates in black alder

Typical properties of black alder are rapid growth in the first decade, slower growth in the mature period, and a short lifetime (Wraber, 1951; Nemesszeghy, 1986; Eschenbach, 1995 and 2000; Herbst et al., 1999; Kecman, 1999; Brus, 2005; DeBell, 2006). After reaching the age of 20 years, a stagnation of growth in height occurs while diameter growth remains satisfactory up into the old age (Giordano and Hibbs, 1993; Middelhoff, 2000; Krstinic et al., 2002).

The percentage of net photosynthesis used for growth and allocation of assimilates to different organs and processes strongly depends on the stand properties including fertility, age, standing biomass, physiological properties, climatic and hydrological conditions, management, and stresses (Chapters 1.2.3.5, 1.2.3.6 and 1.2.3.7), as well as on the social status of individual trees (Giordano and Hibbs, 1993). Stem growth only occurs once the resource demands of foliage and root growth were accommodated (Waring, 1987). Along with increase in stem wood content an increase in maintenance respiration and a decrease in the percent of biomass in leaves were observed (Johansson, 2000).

The research of Eschenbach (1995) studied the distribution of assimilates in 53-year-old black alder. 20,14% of annual NPP (864,4 g/m^2 of carbon) was invested into leaves, 21,93% into wood, 6,07% into annual sprouts, about 9% into growth of “cones” and seeds, about 4,2% into reproductive organs, 1,5% into buds, and 37% into belowground tissue. Altogether annual NPP accounted for 41%, respiration of roots and nodules for 37%, and respiration for 22% of annual net photosynthesis. Lebaube et al. (2000) determined that about 50% of the annual carbon allocation was invested into stem, while 25% was invested into leaves. Middelhoff (2000) and Dilly et al. (2000) discovered that as high as 60% of assimilates were invested into belowground tissues, and about 1/3 of this amount was invested into symbiotic fungi (ectomycorhizal and *Frankia*). Similarly, Kaelke and Dawson (2003) report that nearly half of the new biomass accrued was allocated to roots and nodules. Several researches report that previous estimates on belowground use of assimilates, especially the production of fine roots, were mostly underestimated (Camiré et al., 1991; Middelhoff, 2000; Kaelke and Dawson, 2003).

Production of reproductive organs and seeds is another process that importantly affects the carbon balance of a tree (Waring, 1987; Eichorn et al., 2004). Seed production in black alder is generally high, however, it is not uniform each year (Funk, 1990). Reports on when black alder begins to flower are very different. There are observations that black alder trees begin to flower as soon as in their second to fourth year (Dawson and Gordon, 1979) or as late as at the age of 30 years (Kotar, 2003).

There are researches that discovered high diversity between alder proveniences adapted to different sites (Liepe, 1990). These differences were genetically fixed. The most distinctive differences were observed in the development of root system, but also in radial growth and in growth form.

1.2.3.3 Radial growth

Tree ring widths are affected by a number of cumulative ecological conditions during the vegetation season (Whitehead, 1998; Antonić et al., 1998/99). In contrast to vertical growth, diameter growth depends on current resources, particularly water, it has lower priority for photosynthate allocation, and it is less dependent on genetic records (Kotar, 1979; Waring, 1987; Ogrin, 1989; Knowe and Hibbs, 1996; Carlyle, 1998). Radial growth of individual trees depends on density of trees (Knowe and Hibbs, 1996), on soil water deficit (Giordano and Hibbs, 1993; Bouriaud et al. 2004), it responds negatively to high Vapor Pressure Deficit (VPD), and positively to precipitation and temperature. The effect of temperature is more pronounced on sites with short growing season, whereas water and soil conditions are more important at moderate climates.

In Slovenian climate the radial growth usually begins at the beginning of May and it lasts until the end of August (Kotar, 2003). In diffuse porous species, like black alder and beech, cambium re-activation and bud-burst occur simultaneously and growth follows budburst (Lachaud, 1981, op.cit Lebaube et al., 2000; Lachaud and Bonnemain, 1981 and 1982, op.cit Lebaube et al., 2000). In beech the main part of the radial increment was determined to occur in June (Lebaube et al., 2000). In the research of Kaelke and Dawson (2003) the growth of alder seedlings lasted until November. Black alder, as well as red alder, was observed to allocate a relatively large part of assimilates to diameter growth late in the season (Giordano and Hibbs, 1993).

Black alder is reported to reach diameters up to one meter (maximum diameter recorded in Germany is 1,57 m and in Croatia 1,75 m) (McVean, 1953; Dawson and Funk, 1981; Krstinic et al., 2002). Normally diameters between 35 and 40 cm are reported in Croatia (Krstinic et al., 2002) and in Slovenia (Wraber, 1951) for trees grown from seeds.

1.2.3.4 Vertical growth

Unlike radial growth, vertical growth was discovered to be more dependent on the conditions in the previous growing season (Waring, 1987; Ogrin, 1989; Knowe and Hibbs, 1996), to be relatively unaffected by stand density (Knowe and Hibbs, 1996) and by thinning operations (Johansson 1999a), but it strongly depends on soil parameters (Thibaut et al., 2004). Height growth can be considered an indicator of site productivity of a defined ecological area (Kotar, 2005, p. 185).

Under ideal conditions, growth may be expected to appear as a smooth sigmoid curve (Stahle et al., 1999). European alder usually grows very fast at the beginning and it reaches two-thirds of its maximum height by age 25 (Glavac, 1962). The height growth curve is very steep in the early ages and it soon levels off. Deviations from the “ideal” growth may reflect responses to environmental variations such as fluctuating water levels (Stahle et al., 1999).

Different authors mention different heights that black alder tree can reach. The lowest heights mentioned are up to 25 m (McVean, 1953; Hutchigs et al., 2001; Featherstone, 2003). Other authors report heights of up to 30 m (Brus 2005; Dawson and Funk, 1981); up to 32-33 m (Nemesszeghy, 1986; Eschenbach, 1995), 35 m (Wraber, 1951) or even up to 40 m (Krstinic et al., 2002).

1.2.3.5 Management measures affecting growth

Early, relatively heavy and frequent selective thinnings are usually recommended for black alder stands (Mlinšek, 1961; Kotar, 1986; Kecman and Ferlin, 2001). Heavier thinning especially promotes development of population carriers with the highest diameter rank and development toward more favorable stand composition. Intense changes in the social rank that are taking place in the canopy layer during the development suggest that selective thinning is also appropriate for fast growing species like black alder (Kecman and Ferlin, 2001). However, the thinning should not be too intense, as too hard cuttings could stimulate adventitious branching (Johansson, 1999). Thinning at older ages is not recommended, although even old stands of black alder were discovered to react to moderate tinning measures (Nemesszeghy, 1986; Kecman, 1999).

Natural removal of trees in the lower layers begins quite intensively and early after the canopy closure (Kecman and Ferlin, 2001; Moore et al., 2004; Kotar, 2005; DeBell, 2006). Early thinning should simulate natural process and accelerate growth in the period of the fastest accelerations and the most intense responses to thinning (Kotar, 1979 and 1986; Mlinšek, 1961). The effects of thinning on annual increments and self-thinning rules were studied in several studies of black alder and red alder (Hibbs, 1987; Hibbs et al., 1989; Giordano and Hibbs, 1993; Singh and Thompson, 1995; Knowe and Hibbs, 1996; Knowe et al., 1997; Carlyle, 1998; Kecman, 1999). The majority of researches determined stimulating effect of thinning on the subsequent radial growth of individual trees, whereas effects were considerably less clear for volume increments of standing biomass. Decreases in height growth after thinning were noted in some researches.

The most important response of trees after thinning is increased investment into root and canopy growth (increased Leaf Area Index, LAI; see Chapter 1.2.3.11) (Carlyle, 1998). The time needed to recover a new equilibrium, corresponding to canopy closure, depends on several site conditions and stand properties (e.g. dynamics of canopy and root expansion; Granier et al., 1999). Breda et al. (1995) observed decreases in both interception and transpiration after thinning. On the other hand, Granier et al. (1999) report that transpiration and rainfall interception at a given LAI increased several years after thinning.

If good timber quality is a first priority, Johansson (1999a) advices that alders should be cut when they are 40 to 50-year-old, whereas Wraber (1951) advises final felling at the age of about 50-60 years. Clear-cutting at this age is the most common as it has proven to be the single way for successful regeneration (Forest Management Plans 1971-1980; McVean 1953; Eschenbach, 1995; Herbst et al., 1999).

Clear-cuts usually cause changes in micro-climate, a subsequent increase in mineralization and resulting increased leaching of minerals (Robertson et al., 2000; Zhu et al., 2003; Jacks and Norrström, 2004). On the other hand, some researches indicate that mineral leaching is not very severe below alder (Johnson, 1992; Robertson et al., 2000).

1.2.3.6 Environmental attributes affecting growth

Relative growth rate is importantly affected by both species properties and by environmental conditions. Among tree properties the most important are photosynthetic efficiency of leaves and the ratio of leaf biomass to whole plant biomass, the age of trees and related degree of maintenance respiration. Among environmental parameters that drive changes in net assimilation and respiration rates are light availability, water conditions, temperature, soil fertility (Giordano and Hibbs, 1993; Carlyle, 1998; Snyder et al., 1999; Ogrin, 2000/01; Costa et al., 2003; Horaček et al., 2003; Zhu et al., 2003; Schmitt et al., 2004; Yang et al., 2006), latitude (Valentini et al., 2000), beginning and length of growth season (Kirdyanov et al., 2003), slope (Hendrichson et al., 1993), winter precipitation (Case and MacDonald, 2003), and herbivore attack (Hogg, 1999).

The importance of individual environmental attributes changes during the year, in various climates, and for different species. In the temperate climates the radial increment is usually dependent on spring temperatures (Ogrin, 1989; Schmitt et al., 2004), on temperatures in the previous autumn (Fonti and Garzia-Gonzalez, 2004; Ogrin, 2000/01) or on exceptionally low winter temperature (Kairiukstis and Stravinskiene, 1987), on water conditions during the spring months (Horaček et al., 2003), during the summer (Ogrin, 1989; Fonti and Garzia-Gonzalez, 2004), or in the previous autumn and winter (Costa et al., 2003), and on the amount of reserves deposited in the previous year (Kairiukstis and Stravinskiene, 1987; Schmitt et al., 2004). A wet spring can induce larger investments into root growth and shoot elongation and consequently lower investments into radial growth (Zhang and Romane, 1991; Oliveira et al., 1994). Growth depressions can appear also in periods of low temperature and heavy cloud (DeBell et al., 1996). In the research of Kairiukstis and Stravinskiene (1987) it was discovered that radial increment of trees growing on sites with a constant surplus of moisture was more affected by air temperatures than by rainfall.

The research of Eschenbach (1995) did not show injuries of leaves exposed to temperatures up to 44˚C in the summer. Black alder was also reported to be relatively tolerant to late autumnal and early spring frosts (Cote and Camire, 1984; Johansson, 1999a,b; Vares et al., 2004; Brus, 2005). Reports from the forests under study they did not observe that black alder stands had suffered from white frost in history either (Silvicultural Chronicle, 1971-1992; Forest Management Plans 1959-1968; Nemesszeghy, 1986), even though damages due to late frosts in spring or early frosts in the autumn were frequent in this region. Hendrichson et al. (1993), on the other hand, observed frost damage in frost-exposed stands as well frost-related problems during an alder-breeding program in Japan and in Britain. The absence of important observable damage cannot guarantee the absence of important impacts on the growth processes in this period.

White frost damages a part of leaves and in this way it reduces the production capacity until new leaves are formed. Besides this, construction of new leaves itself is energetically demanding process (Dittmar et al., 2005). Future predictions of phonological models did not forecast any increase in threats due to spring frosts in the lowlands of the temperate climates (Inouye, 2000; Scheifinger et al., 2003; Dittmar et al., 2005).

The major threat for alder is lowering of the groundwater table, which causes a decrease in its ability to compete (Brus, 2004). Effects of water conditions are discussed in the following chapter.

Dozens of insects and diseases were observed on black alder but only a few can cause serious damage. (Nemesszeghy, 1986; Funk, 1990; Brus, 2005). Different researches mention attacks of a leaf-mining sawfly (*Fenusa dohrnii*) (Hendrickson et al., 1991), alder leaf beetle (*Agelastica alni*) (Dolch and Tscharntke, 2000; Kotar, 2003), *Dryocoetes alni*, *Cryptorrhynchus lapathi*, *Croesus septemtrionalis*, *Eryophytes laevis* (Kotar, 2003), and some degree of red deer (*Cervus elaphus*) browsing. Occasional observations of over 140 herbivorous insects were recorded on alder (Featherstone, 2003). The only mentioned potentially more serious threats are a fungus (*Phytophthora* sp.), which kills the roots and bark, and a crown dieback, which results in the tree dying from the top downwards (Featherstone, 2003). At the same time it was discovered that a large part of the decline of black alder stands took place due to application of alochtonous, inappropriate proveniences (Liepe, 1990).

Alder seems to be resistant to chronic ozone fumigation but susceptible to SO_2 damage (Funk, 1990). It is also reported to be sensitive to NaCl, to some arboricides and herbicides (Krstinic et al., 2002).

1.2.3.7 Water conditions and growth

Severe decline in the vitality of black alder stands in south-eastern Slovenia was observed in the middle of the last century (Wraber, 1951; Nemesszeghy, 1986; Levanič, 1993) as well as in several black alder forests in Europe (Pretzell et al., 1997). A decrease in the groundwater table and changes in the groundwater regime and flooding were identified as the most probable reason for this decline (Levanič, 1993; Kazda, 1995; Smolej, p. 39, 1995; Pretzell, 1997; Baar et al., 2002), which is in agreement with drought sensitivity of black alder (Eschenbach, 1995; Hall, 1990). In both stands with low groundwater and in permanently flooded stands alder had lower vitality, lower vertical and radial increments, and it achieved lower biomass (McVean 1953; Levanič, 1993). The abundance of nodules and mycorrhizal rootlets was also lower (Dilly et al., 1999 and 2000; Middelhoff, 2000; Baar et al., 2002).

Notwithstanding the apparently clear causal relationship between the groundwater level and stand vitality (Nemesszeghy, 1986), researches performed until now did not succeed to prove the change in the groundwater level as a major reason for forest decline (Košir, 1987; Levanič, 1993; Levanič and Kotar, 1996; Čater, 2002; Urbančič et al., 2000). Many researches observed decreases in annual increments (Levanič, 1993; Dilly et al., 2000) or increased oscillations in annual increments (Stravinskene, 1982) following a decrease in groundwater table. Drought periods were often found to be a major threat (Giordano and Hibbs, 1993; Schrader et al., 2004). This was especially pronounced in young stands and in shallow-rooted stands (Thibaut et al., 2004), whereas they were not particularly harmful for trees with good developed root system (Waring, 1987).

Water conditions were determined to importantly affect the growth of trees in many researches (Levanič, 1993; Keeland and Sharitz, 1997; Stahle et al., 1999; Čater, 2002). Short-term flooding can increase soil moisture and nutrient deposition, but long-term flooding can have negative effects on forest ecosystems (Kozlowski, 1982). It was found that black alder could hardly resist prolonged flooding (Pretzel et al., 1997; Krstinic et al., 2002; Brus, 2005), especially if it appeared during the vegetation period (Gill, 1975; Levanič, 1993; Kaelke and Dawson, 2003).

The influence of changes in water conditions depends on the location, climate, and on species (Ogrin, 2000/01). Flooding causes oxygen stress in the soil (Kozlowski, 1982; Kairiukstis and Stravinskiene, 1987), increases levels of toxic minerals in the soil (Kozlowski, 1982) and consequent causes decay of roots, reduced nitrogen fixation (McVean, 1953; Iremonger and Kelly, 1988; Kaelke and Dawson, 2003), reduced water and nutrient uptake (Kozlowski, 1982; Stahle et al., 1999), reduced leaf area (Kozlowski, 1982; Seiler, 1985; Kaelke and Dawson, 2003) and decreased photosynthesis and annual increments (McVean, 1953; Kozlowski, 1982; Iremonger and Kelly; 1988; Giordano and Hibbs, 1993; Eschenbach, 1995; Keeland and Sharitz, 1997; Ford and Brooks, 2002; Kaelke and Dawson, 2003). Some researches showed that modifications of hydrologic regime might more importantly affect growth than changes in water level alone (Keeland et al., 1997; Urbančič et al., 2000; Kaelke and Dawson, 2003) and standing water was determined to be considerably more harmful than moving water (Kozlowski, 1982). At the same time changes in the aboveground water level in permanently or periodically flooded sites were discovered to be less important than variations in belowground water level (Keeland and Sharitz, 1997; Stahle et al., 1999). Adult vigorous trees were considerably less sensitive to flooding than seedlings or overmature trees, and flooding during the growing season was more harmful than those during the dormant season (Kozlowski, 1982; Keeland et al., 1997).

After a prolonged flooding, extensive morphological and physiological adaptations take place in trees that are, like black alder, able to live under high groundwater levels (Iremonger and Kelly, 1988; Levanič, 1993; Eschenbach and Kappen, 1999; Keeland and Sharitz, 1997; Schrader et al., 2004; Brus 2005). These adaptations include restructuring of root system, production of adventitious roots (McVean, 1956a; Gill, 1975) and water roots (McVean, 1953 and 1956a; Kozlowski, 1982; Stahle et al., 1999), formation of hypertrophied lenticels in the lower stem and on nodules, aerenchyma formation, transport of oxygen toward roots and into the rhizosphere (McVean, 1956a; Grosse et al., 1992; Eschenbach, 1995; Rusch and Rennenberg, 1998; McCray-Batzli and Dawson, 1999; Dilly et al., 2000), avoidance of accumulation of ethanol and capacity to oxidize the rhizosphere and to tolerate high CO_2 concentrations in the soil (McVean, 1956a; Kozlowski, 1982). In long run these adaptation enable successful growth in inundated stands, but at the same time such stands are more susceptible to drought stress and to wind-throw (Kozlowski, 1982; Stahle et al., 1999) due to shallow root system (Iremonger and Kelly, 1988; Stahle et al., 1999; Middelhoff, 2000; Middelhoff and Breckling, 2005; Dittert et al., 2006). Alternately flooded and drained conditions can result in decreased growth and vitality due to high investments into adaptations (Iremonger and Kelly, 1988; Keeland and Sharitz, 1997; Rusch and Rennenberg, 1998; McCray Batzli and Dawson, 1999; Stahle et al., 1999).

1.2.3.8 Root system

Black alder usually forms two well-developed physiological root types: a surface nutritional system of harder and denser horizontal roots with nodules and mycorrhiza, and a deep-growing system of light senker or tap roots (McVean 1953 and 1956a; Eschenbach, 1995; Eschenbach and Kappen, 1999; Middelhoff, 2000). There is no one main root, but several branched side roots (Brus, 2004 and 2005). The root system is heart-like (Brus, 2005). It is able to extend well below the normal water table (McVean, 1953; Hall and Maynard, 1979, op.cit. Funk, 1990) and to break through very compact soil layers (Liepe, 1990). Black alder is reported to be a deep-rooted tree species (Funk, 1990; Levanič, 1993; Eschenbach, 1995) and it is considered to be one of the deepest-rooting indigenous tree species in Germany (Schmidt-Vogt, 1971, op.cit. Funk, 1990). These deep roots are well situated to use deep-lying soil moisture not available to the upper portion of the root system (McVean, 1953; Hall and Maynard, 1979, op.cit. Funk, 1990) and they enable the trees to be more drought resistant (McVean, 1953). On the other hand, some authors report that in several cases black alders develop shallow root system, especially in flooded stands (Johansson, 1999; Brus, 2005). McVean (1956a), Liepe (1990) and Eschenbach (1995) report that roots of different forms are developed at different growing sites. Considerable plasticity of the root system structure enables the tree to survive on either water logged soils or these with deep water tables (McVean 1953). Liepe (1990) also reports that important differences in root system development exist between black alder proveniences, adapted to the responsive water regime. These differences in results reveal the importance of site-specific evaluations (Stone and Kalisz, 1991).

Roots can grow as soon as the soil is not frozen (McVean, 1953; Middelhoff, 2000) and they are able to grow actively during periods of flooding lasting up to one week (Gill, 1975). Adaptations to flooding were described in the previous chapter. Researches did not succeed to determine a common pattern of root growth dynamics (Camiré et al., 1991; Middelhoff, 2000). Fine root dynamics cannot be explained by phenological stages such as bud break, flowering, or leaf fall, but sometimes fine root biomass may be successfully predicted by climatic variables and nutrient storage pools (Van Praag et al., 1988). Middelhoff (2000) did not find any correlation between groundwater level and annual assimilation, but she observed typical spring and autumnal maxima. Autumnal maxima in root and nodule growth were also pronounced in the research of Kaelke and Dawson (2003).

Root aeration in woody wetland species is not well understood yet (Armstrong and Armstrong, 2005). Black alder stem and roots were reported to have the ability to transport oxygen into roots through thermo-osmotic pressurization (Grosse and Schröder, 1984; Schröder, 1989; Buchel and Grosse, 1990; Grosse et al., 1992 and 1993; Armstrong and Armstrong, 2005; Dittert et al., 2006), however, the importance and extent of this feature are still questionable (Armstrong and Armstrong, 2005; Dittert et al., 2006). The research of Wieβner et al. (2002) discovered that the intensity of oxygen release in marsh vegetation was governed by the size of the above-ground biomass and the intensification of illumination. The influence of photosynthetic intensity (Armstrong and Armstrong, 2005) and the influence of temperature (Schröder, 1989; Dittert et al., 2006) on the intensity of oxygen transportation were stressed also in some other researches.

Black alder invests large amount of assimilates into roots, to the rhizosphere and to mycorrhizae (Dilly et al., 2000). Middelhoff (2000) determined that 60% of annual assimilates were invested into roots, and one third of this was used by symbiotic fungi. Consequently black alder trees importantly affect the composition of microbial communities in the soil and their diversity (Dilly et al., 2000; Featherstone, 2003; Vares et al., 2004). Root exudates and abundant mycorrhizae (Pritsch, 1996; Pritsch et al., 1997; Dilly et al., 2000; Vares et al., 2004) enable the mobilization of phosphorus, whereas *Frankia*-symbionts provide nitrogen to the tree (Dittert et al., 2006). The investment into belowground parts and the intensity of mycorrhiza mostly decrease with an increase in water and availability of mineral nutrients (Dilly et al., 2000; Middelhoff, 2000). The extent of development of nodules and mycorrhiza was also found to be largely dependent on the general well-being of seedlings (McVean, 1956a).

1.2.3.9 Nitrogen fixation and nitrogen in alder tissue

Black alders form a symbiosis with actinobacterium *Frankia* (Nemesszeghy, 1986; Liepe, 1990; Eschenbach, 1995; Johanson, 1999; DeBell, 2006) and with ectomycorrhizal fungi. Without the endophyte or nitrogen the alders do not develop properly (Teissier du Cros et al., 1984; Côté et al., 1989). Permanent nodules grow as a differentiation of roots. The trees provide assimilates, whereas actinobacteria provide the plant with fixed nitrogen (Eschenbach, 1995) and ectomycorrhizal fungi provide phosphorus and other mineral nutrients. The symbiont therefore represent an additional carbon drain to the host plant (Hendrickson et al., 1991). Researches report energy costs of 18,8 g of glucose to fix one gram of nitrogen (Bormann and Gordon, 1984), or 10 g of carbon per gram of fixed nitrogen (Dilly et al., 2000).

The ability of alder species to fix nitrogen can importantly affect stand properties and its fertility (Cole et al., 1990; Funk, 1990; DeBell, 2006), as well as the ability of the species to survive in mineral-poor stands (McVean, 1956b; Eschenbach, 1995; Moffat, 2000). Estimates on the annual nitrogen fixation vary from about 40–45 kg/ha/y (Dittert et al., 2000) to over 300 kg/ha/y (Moffat, 2000; Monzón and Azcón, 2001; Myrold and Huss-Danell, 2003). The most of the nitrogen fixed in the previous growing season is likely to be lost through leaching and flooding during the dormant season (Hurd et al., 2001).

Nodules, despite their low weight, cover an important amount of annual nitrogen demands in alder species. Some studies report that nitrogen fixation can (almost) cover the nitrogen needs of a plant (Mead and Preston, 1992; Baker et al., 1996; Myrold and Huss-Danell, 2003; Vares et al., 2004). Other studies reported that fixed nitrogen covered up to 90% (Gonzalez-Prieto et al., 1995), from 75-80% (Côté and Camiré, 1985) or about 70% (Côté and Camiré, 1984 and 1987; Eschenbach, 1995; Middelhoff, 2000) of required nitrogen. Some studies report that the majority of nitrogen in leaves originates from N_2 fixation (Vogel et al., 1997; Myrold and Huss-Danell, 2003). It seems that that differences in the endophyte as well as genetic variations in hosts are important determinants of symbiotic performance (Gordon and Wheeler, 1978; Dawson and Gordon, 1979).

The intensity of nitrogen fixation is affected by the supply of assimilates to nodules. Côté and Camiré, (1985), as well as Uliassi and Ruess (2002) discovered that the leaf area of the alder canopy is a good predictor of nitrogen fixation. Nitrogen fixation is usually the highest in the time of the highest photosynthetic activity (before midday, in July and August), as well as in better-developed and more vigorous trees (McVean, 1956a; Wheeler, 1971; Gordon and Wheeler, 1978; Dawson and Gordon, 1979; Pizelle, 1984; Funk, 1990; Bormann et al., 1993; Dilly et al., 2000; Hurd et al., 2001). Nitrogen fixation decreases under cloudy weather and lower temperatures, and it ends after leaf shedding or after occurrence of chilling temperatures (Dawson and Gordon, 1979; Côté et al., 1989; Vogel and Dawson, 1991; Ekblad et al., 1994; Hurd et al., 2001). In this way nodules act not only as sites of nitrogen fixation but also as regulators of photosynthetic products (Wheeler and Lawrie 1976, op. cit. Krstinic et al., 2002). It is also hypothesized that the growth and activity of black alder root nodules is sensitive to nitrogen status of the plant (e.g. it decreases after bud removal and increases during growth of catkins) (Pizelle, 1984; Baker et al., 1997).

Nitrogen fixation decreases under low water availability (Shipton and Burggraaf, 1982; Hendrichson et al., 1993; Dilly et al., 2000; Baar et al., 2002). On the other hand, nodules are limited to uppermost layers in inundated soil due to oxygen-sensibility of symbionts (Quispel and Tak, 1978; Shipton and Burggraaf, 1982; Dilly et al., 1999; Hurd et al., 2001; Uri et al., 2002; Gökkaya et al., 2004). Nodules and mycorrhizal rootlets can develop in soils of surprisingly low aeration, though not in completely anaerobic soil (McVean, 1956b; Baar et al., 2002). The nitrogen fixation process can take place when temperatures are high enough (about 15ºC; Rodríguez-Barrueco et al., 1984; Moiroud et al., 1984;

Kaelke and Dawson, 2003) and it is optimal under relatively high temperature conditions (about 30ºC; Buragraaf and Shipton, 1982). The pH range the most favorable for growth of *Frankia* lies between 6 and 8 (Buragraaf and Shipton, 1982), whereas values below 5 generally limit the growth of Actinomycetes.

Despite some opposite results (Cote and Camire, 1984; Baker et al., 1997; Gentilli and Huss-Danell, 2003) nitrogen fixation intensity seems to be independent of the concentration of nitrogen in the stand (Hurd et al., 2001; Bechtold et al., 2003), but it was shown to be dependent on phosphorus availability (Pregent and Camire, 1985; Cole et al., 1990; Wall et al., 2000; Monzón and Azcón, 2001; Uliassi and Ruess, 2002; Gentilli and Huss-Danell, 2003).

The research of Sayed (2003) found that wastewater did not impair *Frankia* growth, despite differences were observed in responses of different *Frankia* strains. They note several reports on the toxicity of other metals on *Frankia* and on plant growth. The research of Baar et al. (2002) has determined negative effects of eutrophication on alder ectomycorrhiza.

Concentrations of nitrogen are different in different black alder organs. Concentration between 0,33% of dry weight (Middelhoff, 2000) and 3,66% (Vogel et al., 1997) are reported for wood (including bark) of alders of different ages (Dawson and Gordon, 1979; Uri et al., 2003a,b). Leaves represent an important part of nitrogen in the plant (Dawson and Funk, 1981). Nitrogen concentrations in leaves are generally higher than in wood (Dawson and Gordon, 1979; Rodriguez -Barueco et al., 1984; Cote and Camire, 1985; Hendrickson et al., 1991; Moffat, 2000; Robertson et al., 2000; Uri et al., 2002 and 2003a,b; Gentilli and Huss-Danell, 2003; Vares et al., 2004) and range from 2,03% (Gentilli and Huss-Danell, 2003) to 5,7% (Vogel et al., 1997). Pizelle (1984) reports concentration of 2,0-2,5% of nitrogen in male catkins, 2,7% in female catkins, and 1,6% in empty dead catkins. Reported concentrations of nitrogen in roots (Vogel et al., 1997; Rodriguez-Baruezzo et al., 1984) are somewhat lower and range from about 1% (Uri et al., 2002) to about 2,5% (Huss-Danell., 2003; *Alnus incana*). Similar values are also observed in nodules: 1,44 % (Rodriguez-Baruezzo et al., 1984) to 1,77% (Uri et al., 2002; Vogel et al., 1976; *Alnus rubra*). Estimations on the concentrations of nitrogen in the whole tree vary from 2 to 3 % (Dawson and Gordon, 1979; Middelhoff, 2000; Uri et al., 2003a,b).

1.2.3.10 Leaf properties

Leaves are the active interface of energy, carbon and water exchanges between forests canopies and the atmosphere (Cutini et al., 1998), and litterfall is a key parameter in the biogeochemical cycle. It links the tree to the water and soil (UN-ECE, 2004a). In general the total amount of foliage increases with the age of trees and is exponentially related to the Diameter at Breast Height (DBH, diameter of a tree at 1,3 m) (Čermak, 1998).

Black alder leaves (Figure 1A) are soft, simple, dark green, with short petioles, rounded to oval, doubly serrated, and distinctly notched at the apex, or blunt when fully expanded (Eschenbach, 1995; Brus, 2005). They have high photosynthetic ability (Eschenbach, 1995 and 1996; Neave et al., 1989; Bonal et al., 2000; Dilly et al., 2000; Schrader et al., 2004), high stomatal conductance and high cuticular evapotranspiration (Levitt, 1980, op.cit. Seiler, 1985), as well as a low degree of stomatal regulation of transpiration (Eschenbach, 1995; Eschenbach and Kappen, 1999; Herbst et al., 1999; Čermák. and Prax, 2001; Schrader et al., 2004). Many researches found that the total evapotranspiration is very high (Hall et al., 1998; Eschenbach and Kappen, 1999; Herbst et al., 1999; Bonal et al., 2000). Black alder is a light demanding tree (McVean 1953; Eschenbach and Kappen, 1999; Eschenbach, 2000). According to the chlorophyll content and the properties connected with productivity, all black alder leaves can be characterized as sun leaves, even though the exposed leaves show somewhat higher specific leaf weight, density of stomata and leaf thickness (Eschenbach, 1995, 2000 and 2005).

Black alder leaves begin to sprout relatively early in the spring and they grow constantly during the year (Dolch and Tscharntke, 2000). New leaves develop well into September (Eschenbach, 1995). The area of leaves follows a curve with optimum, with a maximum leaf area by the middle of the season (Giordano and Hibbs, 1993; Eschenbach, 1995). Inner leaves develop first and they reach smaller final sizes. The outer leaves are still developing, when the inner leaves are already falling (July or August; Kikuzawa, 1980; Hendrickson et al., 1991; Eschenbach, 1995 and 1996; Eschenbach and Kappen, 1996; Dolch and Tscharntke, 2000; Bernal et al., 2003). Some researches regard the summer litterfall (30-50%; Kikuzawa, 1980) as a drought avoidance mechanism (Parker, 1968;

Eschenbach, 1995; Herbst et al., 1999). Others found that the intensity of litterfall most likely depends on the intensity of drought; however, this was not proved yet (Eschenbach, 1995, 1996).

Senescence of black alder leaves begins after the first white frosts. Leaves can be found on trees even in November (McVean, 1953; Neave et al., 1989; Eschenbach, 1995) or December (Pizelle, 1984; Hutchigs et al., 2001; own observations) and they remain metabolically active even until November (Neave et al., 1989). *Alnus* species maintain higher chlorophyll concentrations in leaves until their shedding (Taulavuori, 2006), resulting in prolonged photosynthetically active season (Côté and Dawson, 1986; Taulavuori, 2006). They reabsorb a surprisingly low amount of nitrogen and other nutrients before shedding (McVean, 1953; Dawson et al., 1980; Dawson and Funk, 1981; Côté and Camire, 1985; Côté and Dawson, 1986; Neave et al., 1989; Vogel and Dawson, 1993; Killingbeck, 1996; Kaelke and Dawson, 2003; Vares et al., 2004; Taulavuori, 2006; Hutchigs et al., 2001; Eschenbach and Kappen, 1996).

Early leaf litterfall, nitrogen-rich litter, and very fast decomposition of litterfall (Dilly and Munch, 1996; Dilly et al., 1999; Robertson et al., 2000; Bernal et al., 2003; Vares et al., 2004) facilitate mineral cycles in the stand. The decomposition of litter is also dependent on water availability, temperature, and soil and litter properties (Camiré et al., 1991; Dilly and Munch, 1996).

1.2.3.11 Leaf Area Index and Specific Leaf Area

Leaf Area Index (LAI) stands for the one-sided leaf area per unit ground area (Eschenbach and Kappen, 1996). It is an important parameter of a stand (not of a tree) and it is important in physiological and ecological studies (Köstner, 2001). It is strongly correlated with forest productivity and growth, with intensity of evapotranspiration (ET), with canopy interception (Kotar, 1979; Eschenbach and Kappen, 1996; Whitehead, 1998; Kavvadias, 2001; Samson, 2001) and with stand development. It is an indicator of gap dynamics, canopy development, and disturbance and stress in forests (Waring 1985; Gower and Norman, 1991; Martens et al., 1993; Maitre and Versfeld, 1997; Cutini et al., 1998; Kergoat, 1998; Diaci, 1999; Köstner, 2001; Šraj, 2003; UN-ECE, 2004a).

Litter is a key parameter in geo-chemical cycles, linking the tree part to the water and soil part. LAI plays a key role in interception of radiation, canopy interception, in the carbon assimilation and in ET (UN-ECE, 2004a; Eschenbach and Kappen, 1996). At the same time leaf area is sometimes used as an indicator on nitrogen fixation intensity (Dawson and Gordon, 1979; Côté and Camiré, 1985; Uliassi and Ruess, 2002). Energy and quality of sun radiation regulate many physiological and behavioral phenomena in plants and animals. Indirectly it affects nearly all properites of living and non-living attributes (Diaci, 1999).

LAI depends on stand conditions, especially on its fertility and appearance of drought (Waring, 1987; Köstner, 2001; Šraj, 2003; UN-ECE, 2004a). LAI changes during the stand development, during the vegetation period (Eschenbach, 1995), and during subsequent years (Hogg, 1999). On the other hand, Giordano and Hibbs (1993) report that LAI has stabilized and remained fairly stable once crown closure of black alder trees was achieved.

Eschenbach (1995) notes that LAI changes over the year followed an optimal type curve, with maximum value in August. The LAI values of above 5 or 6 (Eschenbach, 1995; Čermak, 1998; Granier et al., 2000a) were reported to result in increasingly shading of leaves, decreased contribution to carbon assimilation (Čermak, 1998) and decreased understory ET (Samson, 2001).

LAI values betwenn 2,6 and 11 were observed in temperate forests (Jarvis and Leverenz, 1983, op.cit. Gower and Norman, 1991), LAI values up to 6 in mixed forests (Wilson et al., 2001), and values between 2 and 7,5 in different European forests (Valentini et al., 2000; Baldocchi and Wilson, 2001). In comparison to these reports, the LAI values observed in black alder stands were on average relatively low, which could be explained by its pioneer and sun demanding properties. Black alder was reported to have smaller crowns with lower leafing density. The majority of leaves are distributed in the periphery (Eschenbach, 1995, 1996 and 2005; Eschenbach and Kappen, 1996). Eschenbach (1995) determined the maximum value of 4,8 in a 53-year-old black alder stand in Germany in August. Johansson (1999) had determined the mean LAI of 2,85±0,12 for 21- to 91-year-old and (Johansson, 2000a,b), 3,16 for 4- to 36-year-old alder stands in Sweden, and as high as 8,26 in a 36-year-old black alder stand on abandoned land. Estimates on LAI in alder carr woodland in USA were also relatively high, with the estimated LAI of about 5 (Roberts et al., 2001). Vares et al. (2004) determined the LAI of 3,8 to 5,1 in black alder plantations established on a reclaimed oil-shale mining site.

To calculate LAI we have to determine Specific Leaf Area (SLA). SLA is the area of leaves per unit of their mass (m^2/kg) (Šraj, 2003) and it is therefore dependent on the amount of organic matter in leaves. Eschenbach determined SLA values of 12,05 to 17,54 m^2/kg, and Johansson (1999, 2000a,b) values from 12,9 to 16,1 m^2/kg in different black alder stands. Vares et al. (2004) determined SLA between 11,5 and 15,5 m^2/kg in black alder stands, whereas Giordano and Hibbs (1993) measured SLA values of 11,5 to 20,8 m^2/kg. SLA was found to vary in different parts of the crown as well as during leaf development and differentiation (Eschenbach and Kappen, 1996).

1.2.3.12 Evapotranspiration

Evapotranspiration (ET) is the sum of evaporation and transpiration. Evaporation is relatively good understood process of water movement from wet surfaces or from open water surface to the air (Roberts, 1983). Transpiration is more complex and less understood process of losing water vapor through body surfaces, usually from plant tissues.

The most important meteorological and hydrological conditions affecting both evaporation and transpiration are sun radiation intensity, temperature, wind, precipitation quantity and frequency, and Vapor Pressure Deficit (VPD) (Eschenbach et al., 1996; Zhang et al. 1997 and 1999; Eschenbach and Kappen, 1999; Brilly and Šraj, 2000; Goodrich et al., 2000; Samson, 2001). Among stand properties affecting ET the most important is LAI. Transpiration is influenced by many additional factors including several stand properties and tree physiology. The most important stand properties affecting evaporation are the size and age of trees, stand and canopy structure, LAI, soil moisture, and soil type (Dawson, 1996; Breda et al., 1995; Granier et al., 2000a,b; Köstner, 2001; Samson, 2001; Moore et al., 2004). The most important physiological properties are canopy resistance and its regulation, and hydraulic conductivity of plant tissue. Due to its dependence on numerous interdependent parameters the determination of ET remains a difficult task (Köstner, 2001; Samson, 2001; Ewers et al., 2002).

ET is the lowest during the winter (Tognetti and Borghetti, 1994) and it sharply increases in the spring. It remains relatively stable until the beginning of leaf senescence. During the vegetation period the canopy resistance changes in agreement with stomatal resistance of leaves (Goodrich et al., 2000), which is mostly dependent on VPD and water conditions (Köstner, 2001; Samson, 2001). When soil water is plentiful, evaporation generally increases with VPD up to the values, which cause stomatal closure (Wilson et al., 2001) and a consequent decrease in photosynthesis and growth. This correlation is especially important in tree species with high stomatal conductance (Ewers et al., 2002). Transpiration from understory species starts and terminates earlier in the year than transpiration from the canopy layer (Samson, 2001).

When soil water is not limiting, stomatal conductance was shown to increase linearly with LAI values up to 6 and it reached a plateau value at higher LAI values due to the shading of low canopy strata (Granier et al., 2000a). LAI also importantly affects the amount of intercepted precipitation in the canopies (Kergoat, 1998) and the amount of sun radiation that reaches below-canopy strata (Wilson et al., 2000). ET from below-canopy strata is low under canopies with high LAI, but it increases as the LAI declines. Understory ET can therefore be considered as an effective buffer in the canopy differences (Roberts, 1983; Samson, 2001).

Some researches found that the actual evapotranspiration (ET_a) from ecosystems is in agreement with calculated reference evapotranspiration (ET_o) from the reference surface (Čermák and Prax, 2001), whereas ET_a surpassed ET_o in marshes and in some forested ecosystems (Allen et al., 1989; Allen, 1998; Granier et al., 1999; Herbst and Kappen, 1999; Brilly and Šraj, 2000; Köstner, 2001; Andersen et al., 2005). ET_a was also higher from forests than from grass surfaces and from other crops (Lhomme, 1997; Amatya et al., 2000; Zhang et al., 2004). On the other hand, some authors regard ET_o as the upper limit for ET_a (Bidlake et al., 1996), which explains results where measured ET_a values were lower than calculated ET_o (Zhang et al., 1999; Bidlake et al., 1996; Čermak et al. 2001; Campbell et al., 2005). It can be concluded that ET_o is an appropriate estimate of ET_a in ecosystems that are close to the potential conditions (e.g marshes and broadleaved floodplains; Shiau and Davar, 1973; Kuzmin and Vershinin, 1974; Bidlake et al., 1996; Granier et al., 1999; Zhang et al. 1999; see

Chapter 3.1.3), but not in ecosystems in which nonpotential conditions prevail (e.g. dry savanna and coniferous forests; Bidlake et al., 1996; Robin et al., 1998).

Transpiration rates as high as up to 11 mm/day (Eschenbach, 1995; Herbst et al., 1999) were determined in black alder stands under unlimited water availability. Roberts et al. (2001) measured the average transpiration of 2,16 mm/day, with maximum daily rate of 5 mm/day. These values were closer to those recorded for short rotation coppice than for other broad-leaved tree species. In the research of Herbst et al. (1999) the sum of transpiration (389 mm/y) and interception evaporation (128 mm/y) was considerably higher than the average ET calculated for Mid-European forests (333 mm/y; Roberts, 1983). Mid-European forests were discovered to have relatively constant response coefficients for stomatal resistance to humidity deficit (Roberts, 1983); however, it is questionable, whether this could be considered for black alder as well.

The openness of black alder stomata was determined to depend on sun radiation and VPD, whereas no dependence on temperature was found (Eschenbach, 1995). Transpiration rates were, in contrast to the speed of photosynthesis, similar for inner and for exposed leaves: about 2,4 and 2,5 mmol $H_2O/m^2/s$, respectively (Eschenbach, 1996). The highest measured transpiration rates were up to 4 mmol $H_2O/m^2/s$ (Eschenbach and Kappen, 1999). The mean stomatal conductivity of both inner and exposed leaves was between 270 and 230 mmol $H_2O/m^2/s$ in the morning. The maximum measured values were about 350 mmol $H_2O/m^2/s$ and the highest observed value was 1000 mmol $H_2O/m^2/s$), decreasing to about 150 mmol $H_2O/m^2/s$ later in the day. This was considerably higher than are the typical maximum values for woody plants: 190–280 mmol $H_2O/m^2/s$ (Körner, 1994; op.cit. Eschenbach and Kappen, 1999).

Alnus glutinosa reportedly does not control stomatal conductance at low xylem water potential (Eschenbach and Kappen, 1999). Conductance and transpiration are thereby governed by leaf water potential, a strategy that allows maximum productivity when moisture is abundant, while limiting plants to sites where roots can access water (Eschenbach and Kappen, 1999). With summer leaf-shedding black alder trees importantly decrease transpiration of inner leaves with a relatively smaller decline in photosynthetic active surface. In the study by Eschenbach and Kappen (1999) black alder succeeded to resume the leaf water potential in the evening even during drought, and a midday depression of ET was never found in the field studies. These data indicate that deep roots of these trees accessed groundwater.

Comparison of ET_a in black alder and beech stand (Eschenbach et al., 1996) revealed that, although ecological differences, both stands achieved similar summary daily transpiration of about 4 L/m^2/day. Both species responded similarly to the daily sum of photosynthetic photon flux density (PPFD). Average VPD more affected alder due to alder's lower degree of stomatal regulation, but alder leaves achieved their maximum ET at higher sun radiation intensities.

1.3 Dissertation plan

The major purposes that were followed through the research were based on the awareness of the advantages and difficulties of emergy synthesis. The major goals were:

- To determine environmental and management attributes that the mainly determine radial increments in the system under study and to calculate their contribution to the emergy received by the system.
- To build a model that will enable simulations and sensitivity analyses of energy along with emergy flows under different environmental and management conditions over the whole production cycle.
- To present changes in emergy performance indices during the production cycle.
- To identify attributes that present the major threat to the system under study.
- To define guidelines for management with the highest possible degree of sustainability.
- To search for correlations between the magnitude of annual emergy inflows and annual radial increments.
- To enable other improvements of modeling-based emergy accounting (Chapter 1.2.2.1).

Due to the nature of the research several hypotheses are inseparable part of research purposes.

The first part of the research was dedicated to the data assemblage. The data needed were obtained in the site under study. Numerous measurements, tests and analyses were needed before the data were prepared for the major part of research: for data mining, emergy synthesis and model construction. The work was planned as an explicitly interdisciplinary approach.

Machine learning was the next crucial step in the research procedure. It resulted in several sub-models. We expected that at least some sub-models will suitably model radial growth of the trees under study under different environmental and management conditions. Machine learnimg methods were applied it to get new insights about ecosystem function, including identification of attributes that the most importantly affect annual increments and identification of attributes that present the major threat to this ecosystem.

In the following we combined ecological modeling and emergy synthesis to enable the sensitivity analyses of emergy flows and UEVs under different scenarios. We expected that such combinations will be realizable and that they will result in interesting findings. Our goal was to test whether the most important attributes were at the same time the carriers of the highest emergy flows driving the system and whether changes in emergy flows cause proportional change in annual increments. We hypothesized that two outcomes are possible: higher emergy inputs can cause higher annual increments or there can be an optimal value of emergy input, above which the excess emergy causes stress. Besides, we expected that it will be possible to identify impacts of individual emergy flows and to determine attributes that are the most important for further prosperity of these forests. One of our important expectations was that it will be possible to evaluate influences of management on ecosystem function.

2 SITE DESCRIPTION

Complex ecological laws and thermodynamic principles had to be accounted for in the process of choosing an appropriate study case. We were searching for a natural system, capable of self-recording long-term annual biomass production, as one of the most reliable indicators of ecosystem function. We needed an attribute that would perceive changes in the ecosystem, which appear due to management or other human influences. This would offer a possibility to evaluate effects of human-induced and other environmental disturbances on the capability of the stand to use available energy resources (according to the Maximum Power Principle).

Forests have an important characteristic, which was prominent for our purposes. They have a kind of a self-registering mechanism on the ecosystem function: the annual tree-rings. Knowledge about the high complexity of interactions within forest, diverse plant responses, and attainability of the past meteorological and hydrological data were crucial factors in the process of choosing appropriate research case.

2.1 Study site

Review of several different possibilities, advantages and limitations was needed to choose appropriate study case. We selected homogenous, even-aged, monospecific black alder (*Alnus glutinosa* (L.) Gaertn.) stand in the Forest Unit Mala Polana in the southeastern part of Slovenia (Figure 2). The research plot was located in the forest stand 72B, which has the area of 21,17 ha. With 69 years this stand already surpassed its maturity and part of it was cut down in January 2005 (Figure 3). The research plot had latitude of 46,595, longitude of 16,358 and altitude of about 165 m (Figure 2). It was part of 414 ha of black alder forests Polana on the left side of the Ledava River.

In these stands two-year-old plantings are planted with a density of 3000 plantings per hectare nowadays (Kecman, 2004, personal communication). Due to abundant undergrowth its harvest is needed 2-4 times before the canopy closure. The first thinning is usually performed when trees are about 5 m high (at the age of about 6 years), and the next thinnings at each 3 to 4 m of height growth. Two thinnings should be performed until the age of 10 years, and two additional moderate thinnings should be performed until the age of 20 years (Kecman, 1999; Forest Management Plans, 1992-2001).

Back alder was the most numerous species in the stand under study (85%), followed by ash (*Fraxinus angustifolia*; 12%) and oak (*Quercus robur*; 3%) (Nemesszeghy, 1986). The trees surpassed the height of 30 m in our stand (Nemesszeghy, 1986; Laganis J., unpublished data; Figure 4) and consequently these stands can be classified as the best black alder sites. Black alder here forms a natural community that is stable over a long run (Culiberg and Šercelj, 1990). This community (*Carici brizoidis-Alnetum glutinosae*) is regarded as the climax community in this area.

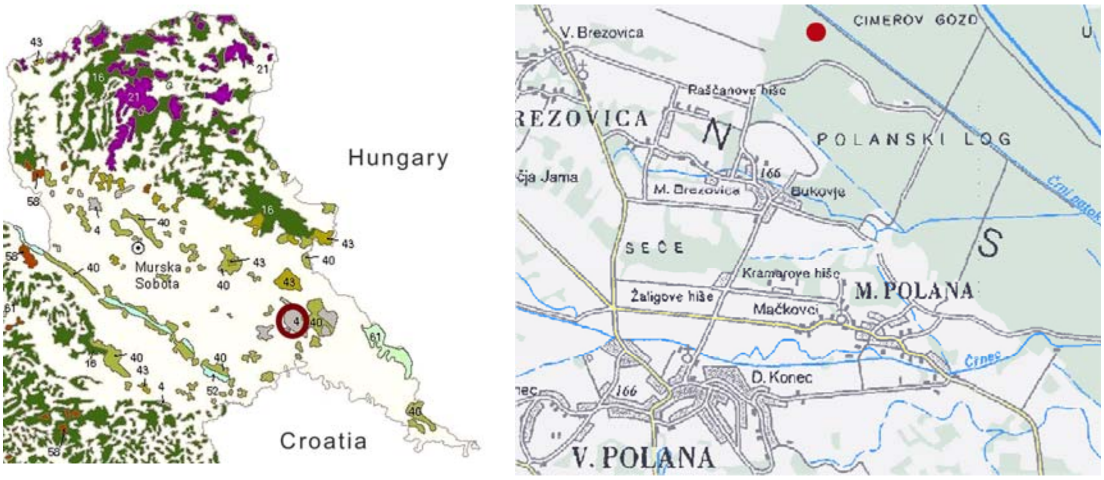


Figure 2 *The position of Mala Polana on the vegetation map of the southeastern Slovenia (left) and a map in higher resolution showing position of the research plot (red circle).*

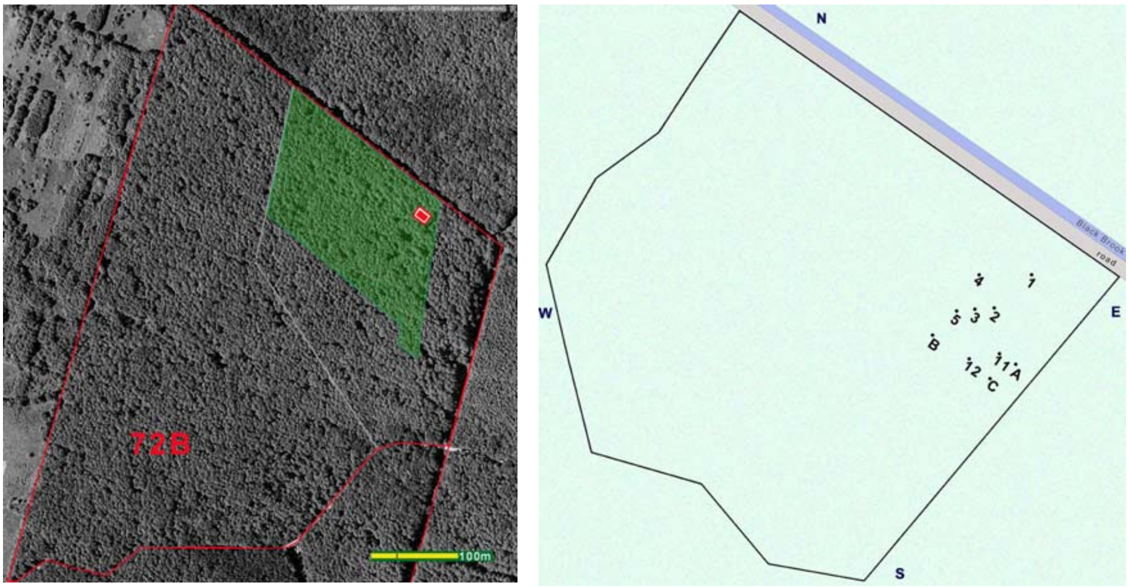


Figure 3 *The part of stand 72B that was cut down (green area) and the position of the selected trees (red square) (left). Position of the selected trees in the stand under study (right).*

Figure 4 *The alder stand 72B at Mala Polana before (left) and during the final cut (right).*

Important properties of the stand under study were:

- The beginning and the end of the production cycle were known.
- The stand was fully developed. The felling was performed between 19th and 24th January 2005.
- High water level was a reason for relatively rare water shortages.
- Productive soils (Nemesszeghy, 1986; Levanič, 1993).
- The flat ground eases calculations of the amount of received solar energy, wind energy and the amount of precipitation. Moreover, even and flat landscape promises adequacy of the data from the meteorological station in Lendava and the hydrological station in Čentiba for our stand.

The Forest Unit Polana is a part of the Natura 2000 network as a Proposed Site of Community Importance (pSCI) and as a Special Protected Area (SPA), based on Birds Directive. It is declared as an ecologically important area Floodplain Forests near the River Ledava, and as a natural value at the state level. The Ledava and other streams are categorized as technically regulated waters.

2.1.1 Climate and soil conditions

The selected site lies in a Panonic type of climate with dry and hot summers and cold winters. Mean annual temperature is 9-10°C. Important for the vegetation are frequent frosts late in the spring (Wraber, 1951). In the period under study white frosts did not appear later than in April.

The average amount of precipitation is below 800 mm (ARSO, Wraber, 1951), somewhat less than 60% of which falls during the growing period (Žiberna, 1992). In an about 5 km distant upstream well the annual groundwater level amplitude of about 1,15 m was determined between 1953 and 1992 (Smolej, 1995, p. 39). This well has a similar distance to the Ledava River as our stand.

The most important attributes determining the future of these forests are water conditions: soil water levels and flooding. Soil water is standstill or it flows very slowly through a gravely substrate (Wraber, 1951; Levanič, 1993). Previous researcesh confirmed the close link-up and synchronous fluctuations between the Ledava River level and the groundwater level (Levanič, 1993; Smolej, 1995). In our stand the groundwater level was relatively high. During the measuring period it was quite close to the surface (0 to 80 cm). At times the stand was also partly overflown.

This flat area has gravel-sandy quaternarian siliceous grounding, which was deposited by the Ledava River and its tributaries from the Goričko Hills. These deposits are in places covered by an impermeable layer of clay or silty-sandy clay. Deposits are covered with fertile, clayey alluvium (intrazonal type of soil, hypogleic eugley; Wraber, 1951; Kalan, 1988; Urbančič et al., 2000). This alluvium varies in depth, but it is generally relatively shallow (Wraber, 1951; Levanič, 1993). A shortage of limestone through the whole soil profile is a reason for poor physical and chemical soil properties (Wraber, 1951). Ascendant groundwater flows toward the surface (upward) are prevailing during the vegetation period and consequently the soil is rich with mineral nutrients (Kalan, 1988). Nitrogen in the soil is reported to be abundant (Kalan, 1988; Levanič, 1993).

2.1.2 Historical background of the study area

Homogenous black alder forests in the lowlands of northeastern Slovenia are among the last remnants of natural and homogenous black alder wetland forests in Europe. The area was covered by alder and oak forests and it was partly uncrossable in the 18th century due to high water levels (Wraber, 1951). In 1814 and in 1919 two parallel channels were built which drained the area and assured new area for agricultural production (Forest Management Plans, 1992-2001). Later on rivers and streams were meliorated several times and some additional draining channels were built before and after the Second World War. After 1970 extensive regulations were performed on the Ledava River. In 1980 a reservoir at Radmožanci was constructed to direct high water of the Ledava River to the forest to protect the town Lendava from floods. At the same time the riverbed of the Ledava River was deepened and several deep draining channels were excavated (Forest Management Plans, 1992-2001). During this time a large extent of forests was cleared to obtain land for the agricultural production (Nemesszeghy, 1986; Levanič and Kotar, 1996; Čater, 2002).

A consequence of meliorations was a decline in the groundwater table. Smolej (1995) reports that between 1953 and 1992 (40 years) the groundwater has decreased for 60 cm. 50 cm of this decrease took place during the last 20 years. The rhythm of flooding has changed as well. The natural flooding in spring was halted (Kalan, 1988; Čater 2002) and an artificial flooding in the spring or summer was introduced (Kalan, 1988; Levanič, 1993; Levanič and Kotar, 1996). Black alder forests remained only on soil, which were inappropriate for agriculture due to high groundwater or low fertility (Nemesszeghy, 1986). Forest coverage has decreased to less than 20% of their former area nowadays (Levanič and Kotar, 1986; Forest Management Plans, 2002-2011).

In parallel with meliorations a decrease in the vitality of many the remaining stands was observed (Wraber, 1951; Forest Management Plans, 1971-1980; Nemesszeghy, 1986; Levanič, 1993; Urbančič et al., 2000), although this decay was somewhat less pronounced in Forest unit Polana in comparison to other forests in this area (Wraber, 1951). Previous studies (Levanič, 1993; Čater, 2002) discovered that annual increments of trees in this area became more diverse after meliorations.

Slovenian lowland forests and especially black alder (*Alnus glutinosa* (L.) Gaertn.) stands were rarely studied in Slovenia (Nemesszeghy, 1986; Levanič, 1993; Kecman, 1999a and 1999b; Torelli, 2001). Some researches on alder stands were done in Germany and in Scandinavian countries (Eschenbach, 1995, 1996, 1998, 2000; Eschenbach and Kappen, 1996 and 1999; Eschenbach et al., 1996; Middelhoff, 2000; Johansson, 2000; Kutsch et al., 2001; Eschenbach and Middelhoff, 2001; Baar et al., 2002; Schrader et al., 2004).

3 METHODS AND DATASETS

The comprehension and purposes of the study demanded examination of several different datasets (attributes), their importance, interdependence and connectedness. The attributes describing stand structure and annual increments were obtained through measurements in the selected stand and through the subsequent dendrochronological analysis. The others were obtained from forestry, meteorological, and hydrological institutions. All of them were used as input data for the major part of this research: emergy synthesis and modeling. Consequently we present both the methodology for the data acquisition and measured values in the first part of this chapter.

In the following the chapter presents methods that were applied to reduce the number of attributes with the highest likelihood to affect radial increments and machine learning methods needed to define correlation between selected attributes and resulting radial increments. The chapter continues with emergy accounting results and it ends with the description of the structure and validation of the constructed model.

3.1 Dataset

The dataset (attributes) used in the study can be classified into three groups. The first group included the data on the growth of eight individual trees in the selected forest stand, the second group comprised meteorological and hydrological data, and the third group contained the data about the forestry management measures performed in the selected forest stand. All three types of the data were available for the period of 35 years (1970-2004), with the exception of the data on groundwater levels that were available only for the last 25 years.

3.1.1 Stand characterization and dendrochronology

The data that were obtained through the stand characterization included the number of trees in the stand, their Diameter at Breast Height (DBH), heights of a sub-sample of trees, and LAI determined in 2004. Besides this, we noted also the data on the vitality and the social status of all trees in the stand.

Measurements were performed in November 2004. The selected research plot had the area of 0,97 ha and all the data were recalculated to the area of one hectare in the subsequent work. The measurement and the visual assessment of stand conditions was based on recommendations written in the Manual of the United Nations Economic Commission for Europe (UN-ECE, 2004b and c):

- The DBH was measured with the diameter tape on all trees in the stand with a diameter larger than 5 cm. 397 trees were measured (schoolmarms were considered as single trees; UN-ECE, 2004c).
- Measurements of tree heights were done on a sub-sample of 140 trees with different DBHs.
- According to their social status the trees were divided into five classes: dominant, codominant, subdominant, suppressed and the trees from the lower stratum.
- Crown width, crown depth, crown symmetry and vitality were estimated optically and classified into the following classes: 1 (narrow) to 5 (wide) for canopy width; 1 (low) to 3 (high) for the canopy depth; 1 (symmetric) to 3 (distinctly developed in one direction) for the crown symmetry; 1 (highly vital) to 6 (dead) for the vitality of the trees.

These data were used to determine the average volume of standing biomass. Additionally, 10 trees were selected in the inner part of the stand for further analyses. We measured tree height, height to crown base, DBH, and mutual positions of these trees.

Ten trees were cut down in January 2005. Stem disks were taken from ten neighboring trees for the dendrochronological analysis. All trees were from the dominant social layer (according to the classification of UN-ECE, 2004c). About 5 cm thick sections of timber offcuts were obtained from 8 to 10 different heights (Table 1). The stem disks taken from the first level were used in determination of radial increments of the trees, whereas the data on radial increments on all levels were used in determination of height and volume increments. The stem disks were air-dried and prepared for the dendrochronological analysis. Two trees showed deformations in their growth (rotten core or broken top of the tree) and they were consequently not included into the further analyses.

3.1.1.1 Leaf Area Index determination

Despite several different methodologies exist for the Leaf Area Index (LAI) determination in forests, reliable estimation remains an important logistical problem (Šraj, 2003). The most common direct methods are the destructive harvest of leaves, sapwood area to leaf area estimates (Martens et al., 1993), and leaf litter collections. The method based on litter collection is most directly related to the LAI (Cutini et al., 1998). As direct methods are often laborious and time consuming (Gower and Norman, 1991; Welles and Norman, 1991; Planchais and Pontailler, 1999; Šraj, 2003), several indirect methods were developed like measurements of fractional light penetration through the plant canopy (Martens et al., 1993), canopy photography (hemispheric photography; Diaci et al., 1999; Diaci and Kolar, 2000; Planchais and Pontailler, 1999), analyses of gap fraction data (e.g. Decagon Ceptometer, Li-Cor Line Quantum Sensor, Li-Cor LAI 2000 Plant Canopy Analyzer; Gower and Norman, 1991; Welles and Norman, 1991; Fassnacht et al., 1994; Cutini et al., 1998; Diaci, 1999), and computerized digitalization. No one of these methods proved to be reliable in all meteorological and stand conditions, and there is a question about the comparability of results among instruments in all cases (Martens et al., 1993; Cutini et al. 1998; Diaci, 1999; Diaci et al., 1999; Šraj, 2003). Direct methods are still needed at least for a calibration (Martens et al., 1993; Eschenbach and Kappen, 1996; UN-ECE, 2004a). The leaf collecting method is still one of the most frequently used methods (Eschenbach and Kappen, 1996; Cutini et al., 1998; Kavvadias et al., 2001).

In the LAI determination and in the leaf sampling we followed the guidelines noted in UN-ECE Manual on Methodology (UN-ECE, 2000; UN-ECE, 2004a). Ten leaf-collectors were placed randomly within the stand in September 2004. Leaf collectors were made of wire mesh with the mesh size of about one centimeter (Fig. 5). A plastic mesh with pore diameter of about 4 mm was inserted and fixed into the wire frame. The horizontal area of a separate trap was 0,336 m^2 and its height was 0,2 m. Collectors were raised above the soil to avoid flooding. The opening area was horizontal. Traps were fixated in the soil to prevent movement. Each of them was labeled with the number and an appropriate stand mark. Traps were set up at least 30 m from the stand edge to avoid edge conditions.

Leaves were collected on 11th November and on 10th December 2004. In the autumn 2004 leaf falling was late due to warm autumn. At the time of first collecting about 40% of leaves were still on trees.

In the drying, weighing and storing procedure we regarded guidelines in the UN-ECE Manual (UN-ECE, 2004a). Leaves and other plant remnants were air-dried and sorted by species. We divided plant remnants of each species into three categories: foliage (and separately foliar petioles for ash), wood (bark, branches, twigs etc.), fruits, cones and seeds. After the sorting samples were dried in the oven at 80˚C until constant weight. 48 hours were usually sufficient. After the drying the leaves were weighted.

Figure 5 *Leaf collectors: empty (left) and in the time of leaf falling (right).*

Funk (1990) noted that alder's leaf litter readily gives up water-soluble substances and it can loose up to 12% of its weight after just one day's leaching in cold water. This weight loss was taken into consideration in calculations.

To determine mean annual specific leaf area (SLA; leaf area per unit of dry leaf) we weighted a sub-sample of unwrinkled and undamaged leaves with known area. For this purpose the area of 200 fresh alder leaves and 150 fallen alder leaves was measured. Fresh alder leaves were taken partly from lower branches exposed to sun and partly from leafed branches that fell from the crown (leaves were still fresh and green). Leaf area was measured with the Delta T areameter (Delta T Devices Ltd., Cambridge, UK) at the Biotechnical Faculty in Ljubljana.

From the proportion between the mass and the area of leaves we calculated SLA of 0,32 kg/m^2. SLA was used to transform leaf biomass into LAI. The average LAI of 6,8±0,9 was calculated from ten samples (ten leaf collectors).

3.1.1.2 Radial growth

Tree-ring widths are traditionally used as the main feature to describe radial growth (Fonti and Garzia-Gonzalez, 2004) and time series of dated annual rings are used to analyze relationships between tree-growth and climate and to reconstruct past climates.

The data on the radial growth increments were obtained from the eight cut trees. Those trees were of approximately the same age. The stem disks were relatively symmetric (equally developed) in all directions. After air-drying, the stem disks were prepared for the dendrochronological analysis. Firstly about 4 cm wide cutting outs were sawn out of the bigger stem disks to reduce their size. After that the samples were sanded and polished with the grit abrasive paper to clearly distinguish ring boundaries. Annual increments were measured to the nearest 0,01 mm using a LINTAB measuring stage, PAST4 software and a dissecting stereomicroscope Olympus SZ-CTV (SZ-60) with video display. On each stem disk measurements were done in two different directions and their average was used in the calculations. The chronologies of the individual trees were cross-dated to identify possible measuring mistakes or growth particularities like locally absent rings or false rings.

The average radial increments of eight stem disks, which were taken from the DBH level, are shown in the Figure 6. The adequate radial increments of individual trees are presented in the Appendix A (Figure A1). In agreement with the common dendrochronological practice we studied samples taken from the breast height (Kotar, 2005, p. 210; Levanič, 2005, p.25), despite the best sampling location is usually somewhat higher, i.e. at about 1/5 of the tree height (Levanič, personal communication, 2007).

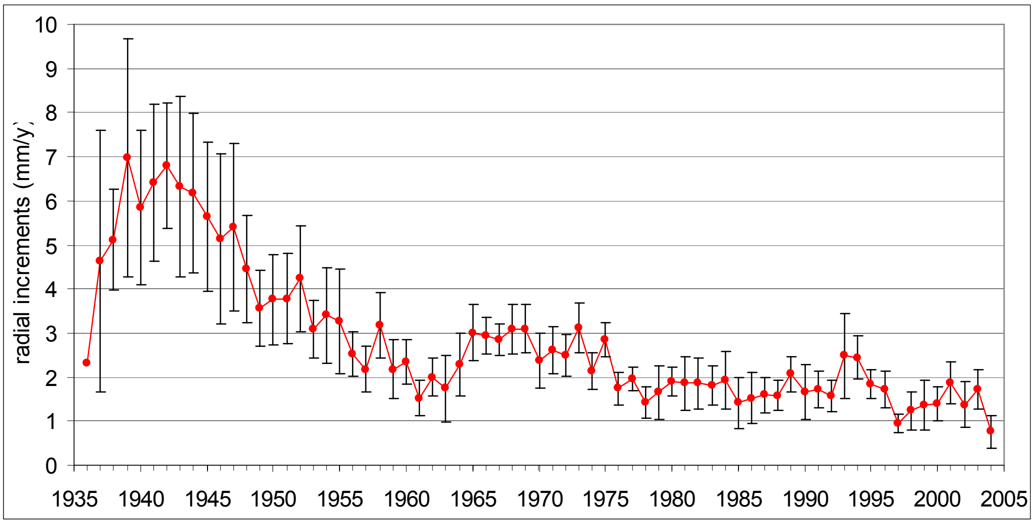


Figure 6 *Average radial increments of the eight trees under study over the whole life cycle (mm). Vertical bars indicate standard deviation (SD).*

To determine trends in the radial growth we calculated moving averages for average increments of the trees over the whole life period (Appendix A, Figure A2). We used the averaging period of 5 years (the current year ± 5 years). The data are shown in the Figure 7.

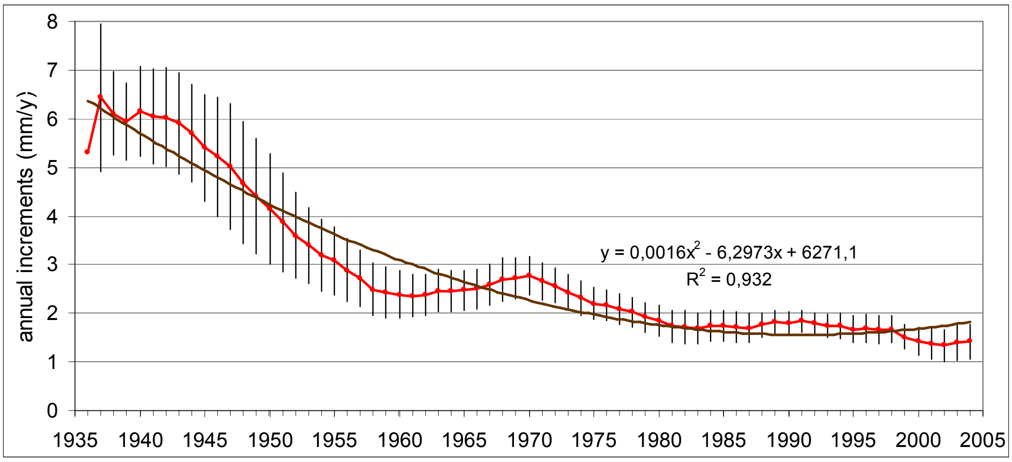


Figure 7 *The moving average increments of average radial increments of the eight trees with noted polynomial regression curve, regression correlation coefficient and standard deviations (vertical bars).*

The data on fresh diameters were unfortunately available only for 6 out of 8 trees under study due to the accommodations that were needed at the time of felling. Radial increment values measured during the dendrochronological analysis were somewhat lower than the values of initial DBH of the standing trees due to the shrinkage during the drying and due to the omission of the bark thickness in dendrochronological measurements. The average decrease in diameters due to the drying and due to the release of bark thickness was 16% (ranging from 10,9 to 20,6%). Deviations in shrinkages were partly caused by possible differences in height and orientation of sampling location of both measurements. The comparison of diameters measured at DBH on the standing trees and the diameters calculated during dendrochronological measurements of annual increments is presented in the Figure 8.

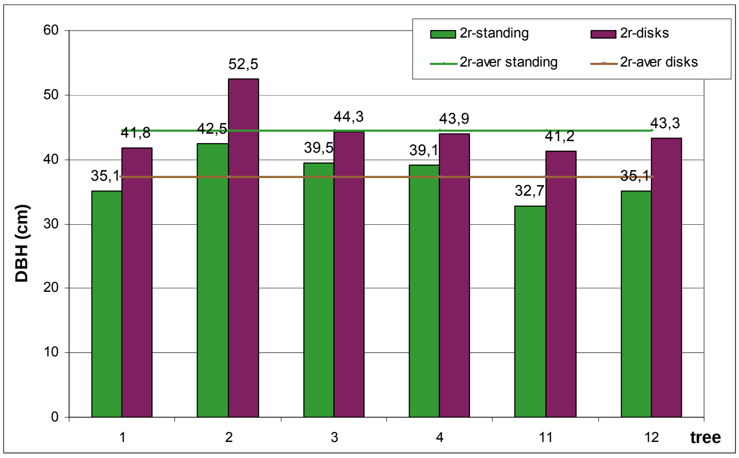


Figure 8 *The comparison of diameters of six trees measured at DBH before (2r-standing; cm) and after felling and air-drying (2r-disks; without bark; cm). The average diameter of the standing trees (2r-aver standing) at the DBH and the average diameter of the stem disks from the level 1 (2r-aver disks) are marked as well (cm).*

3.1.1.3 Height growth

Heights of 140 standing trees were calculated from the data on the angle between the bottom and the top of the tree (measured using a clinometer) measured from a known distance. The distance from the tree was measured with a measuring tape. It is adviced that height should be measured at least for trees that form 5% of the basal area (UN-ECE, 2004c).

The heights of the cut trees were measured with a measuring tape. The comparison of heights measured in both ways is presented in the Figure 11. Three heights measured with the clinometer were missing due to accommodations needed at the time of felling.

The data for annual height growth increments were obtained through the stem analysis procedure, as it is described in the UN-ECE Manual (2004c). Eight to ten stem disks were taken from each tree as well as total height of each tree was measured. Heights from which individual disks were seized and total heights of the sampled trees are noted in the Table 1. From the difference in the number of annual rings between two successive disks it was possible to determine how many years the tree needed to grow for the adequate height. The annual height growth increment was determined as the height increment between the two successive stem disks divided by the number of year needed. In this way we got average annual increments, which are called 'measured' in the following.

Average height increments over the whole life cycle are presented in the Figure 9. The height growth of the individual trees over the period of 35 years is shown in the Appendix A2. In this appendix the Figure A3A presents measured height increments and the Figure A3B presents modeled height increments. The comparison of average growth curves determined in both ways is shown in the Figure 10. The same figure indicates heights that would be provided for trees growing on sites with site indices 26 and 28 (Kotar, 2003; modified from Halay et al., 1987).

Secondly, we fit the polynomial regression equation to each of these height growth curves. The second order polynomial equations were appropriate for growth curves of six trees, whereas third order equations were chosen in two cases (trees 3 and 11; Table 2) because the increase in the equation order importantly improved regression correlation coefficients. Equations were generated on the data on height increments of the individual trees in the last 45 years before the trees were cut down. This was the period in which we expected available meteorological data. The data on height growth increments calculated from regression equations are called 'modeled' in the following.

Table 1 *Heights on each tree from which the stem disks were seized and total heights of the sampled trees (m).*

Level (m)	Tree 1	Tree 2	Tree 3	Tree 4	Tree 5*	Tree 11	Tree 12	Tree A*	Tree B	Tree C
height of disk 0	0,3	0,5	0,4	0,3	0,6	0,7	0,3	0,4	0,7	0,5
height of disk 1	1,3	1,3	1,3	1,3	2,0	1,3	1,3	1,4	1,3	1,3
height of disk 2	5,5	4,7	5,4	5,4	4,9	4,3	5,4	5,4	5,4	5,4
height of disk 3	9,5	8,8	9,5	9,4	8,9	8,4	9,5	9,8	9,5	9,5
height of disk 4	13,8	13,2	13,6	13,5	13,1	12,6	14,1	13,7	13,6	13,6
height of disk 5	17,1	17,0	17,6	17,4	17,2	15,8	18,5	16,6	17,4	18,2
height of disk 6	20,0	21,7	19,8	20,0	20,1	19,0	21,6	18,0	21,7	21,1
height of disk 7	23,4	23,8	22,5	24,1	23,1	22,2	24,2	20,3	24,0	23,6
height of disk 8	24,8	26,6	24,3	24,6	24,9	24,9	25,9	22,2	26,0	25,8
height of disk 9		28,5	25,7	27,3	27,0	27,3	27,4	24,1	27,9	26,5
height of disk 10		29,9	27,4			28,0	28,5		28,7	27,3
Total tree height	27,1	30,3	29,6	30,2	28,9	29,5	30,2	26,1	30,3	29,2

**Results of trees 5 and A were not considered in the further research due to growth anomalies of these trees.*

Table 2 *Regression equations of height growth increments of the trees under study. Equations cover height increments in the last 45 years.*

Tree	Polynomial equation used	R^2
1	$h = -0{,}000774x^2 + 0{,}237917x + 14{,}498560$	0,995
2	$h = -0{,}004880x^2 + 0{,}670391x + 7{,}377561$	0,990
3	$h = -0{,}0001056x^3 + 0{,}0162873x^2 - 0{,}6149925x + 29{,}1287815$	0,988
4	$h = -0{,}001004x^2 + 0{,}342816x + 11{,}671329$	0,978
11	$h = 0{,}0002491x^3 - 0{,}0426264x^2 + 2{,}5030777x - 21{,}9427596$	0,997
12	$h = -0{,}0017273x^2 + 0{,}3429707x + 14{,}7504029$	0,993
B	$h = -0{,}0013089x^2 + 0{,}3457712x + 12{,}8677809$	0,997
C	$h = -0{,}0019473x^2 + 0{,}3611633x + 13{,}5128943$	0,999
Average tree	$h = -0{,}002219x^2 + 0{,}410238x + 11{,}839212$	0,998

R^2: regression correlation coefficients between measured and modeled values.

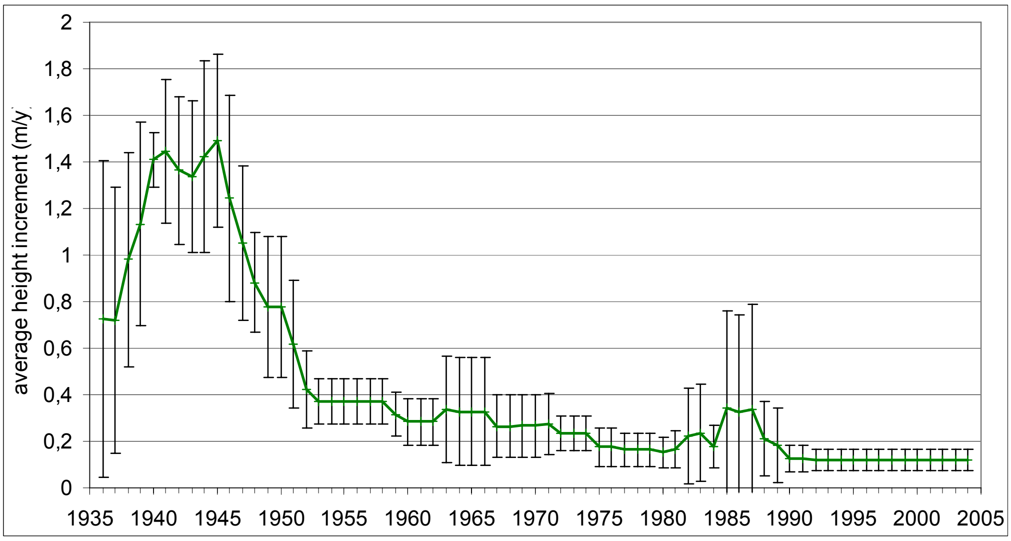


Figure 9 *Height growth increments: Average "measured" height increments of eight trees with marked standard deviations; the data for the whole life cycle of the trees (69 years).*

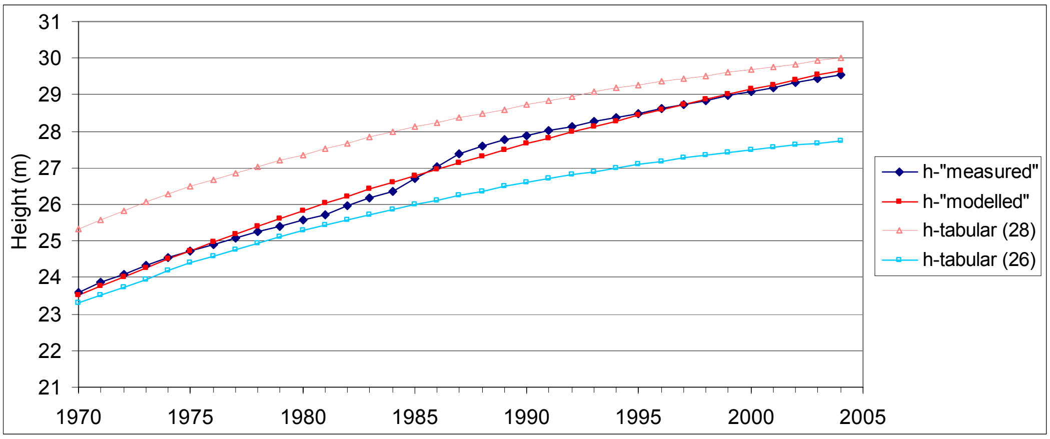


Figure 10 *Height growth: the comparison of average measured and average modeled growth curves, heights predicted in yield tables for black alder trees growing on sites with site index 26 (h- tabular (26)) and site index 28 (h- tabular (28)); the data for the period of 35 years.*

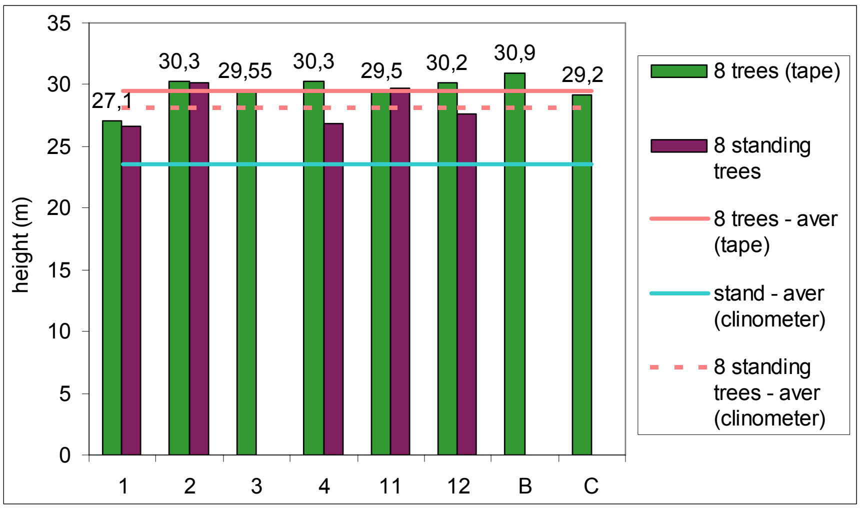


Figure 11 *The comparison of heights of eight cut trees measured with the measuring tape (8 trees (tape)), their average (8 trees-aver (tape)), and heights of these trees measured with the clinometer (8 standing trees, 8 standing trees-aver (clinometer)). The average height of 140 black alder trees measured with the clinometer is marked as well (stand-aver (clinometer)). Numbers above the columns indicate heights measured with the measuring tape after felling.*

3.1.1.4 Volume increments

Volume increments were calculated in three different ways:

- From the data on annual radial and height increments. During this calculation we considered trunks between the successive stem disks as truncated cones, whereas the uppermost part was considered as a cone. In this way we calculated increments of the trunk volume (without branches). We applied measured diameters and measured heights in the first case and measured diameters and modeled heights in the second case.
- Using the Puhek's equation (Kotar, 2003) for stemwood (eq. 1; parameters a)) as well as for total tree biomass (eq. 1, parameters b)). In both cases volumes were calculated over the whole growth cycle of the trees using measured diameters and modeled heights.

$$V(m^3) = a_o{*}d{*}h+a_1{*}d{*}h^2+a_2{*}d{*}h^3+a_3{*}d^2{*}h+a_4{*}d^2{*}h^2+a_5{*}d^3{*}h+a_6{*}d^3{*}h^3+a_7{*}d^4{*}h^2+a_8{*}d^5{*}h^3 \quad (1)$$

a) Stem biomass

a0	a1	a2	a3	a4	a5	a6	a7	a8
-0,5501248	0,029872117	-2,16E-04	7,65E-02	-1,66E-03	-4,46E-04	4,89E-07	2,92E-07	1,40E-10

b) Wood biomass

a0	a1	a2	a3	a4	a5	a6	a7	a8
2,1E-03	8,9E-03	-1,3E-04	2,8E-02	-3,6E-04	9,3E-04	3,1E-07	-1,1E-06	3,5E-10

In all cases the data on the diameters of air-dried stem disks without bark and the data on heights of the stem disks were used (Table 1). Consequently the results were 30% lower in comparison to the results obtained from standing trees.

The comparison of the average annual volume increments and the average volume of the trees are presented in the Figure 12. Volume increments of the individual trees calculated in all three ways are presented in the Appendix A, Figure A4. Comparisons of average volume increments and average standing volumes calculated in all three ways are presented in the Figure 13 and in the Figure 14. The data calculated with measured and modeled heights were in good agreement, whereas somewhat higher discrepancies were observed when we used the Puhek's equation.

High was also the disagreement between volume incremetns calculated in the present study, values predicted in the Yield Tables (Kotar, 2003, modified from Halaj et al., 1987), and values noted in the Forest Management Plans (1956-2011) (Figure 13). Values noted in the Forest Management Plans (red squares) were either lower or higher than the results of this study. Also the comparison of our calculations on standing mass and the corresponding data from the Forest Management Plans (Figure 14; red squares) revealed quite important discrepancies. Differences observed in comparison of standing volumes calculated in the present study and adequate values predicted in the Yield Tables (Figure 14, curves e), f) and g)) imply that our stand has undergone transition from the stand with the site index below 26 to the stand with the site index higher than 28. However, we shouldn't forget that we did not work on the highest trees in the stand (although all of them had canopies in the uppermost layer) and consequently some differences may appeared due to the measurement bias. Moreover, the Forest Management Plans (1982-1992) already report that applied Yield Tables (Schwappach, Pressler, Böhm-Heyer) underestimate the volume of the standing wood.

The goal of the management is to harvest approximately the same amount of wood during the production cycle and at the final felling. In our case the amount of wood removed during the thinning measures was somewhat below the plans (Figure 15) whereas the volume of standing wood surpassed the planned volume of 325 m^3/ha (Forest Management Plans, 2002-2011).

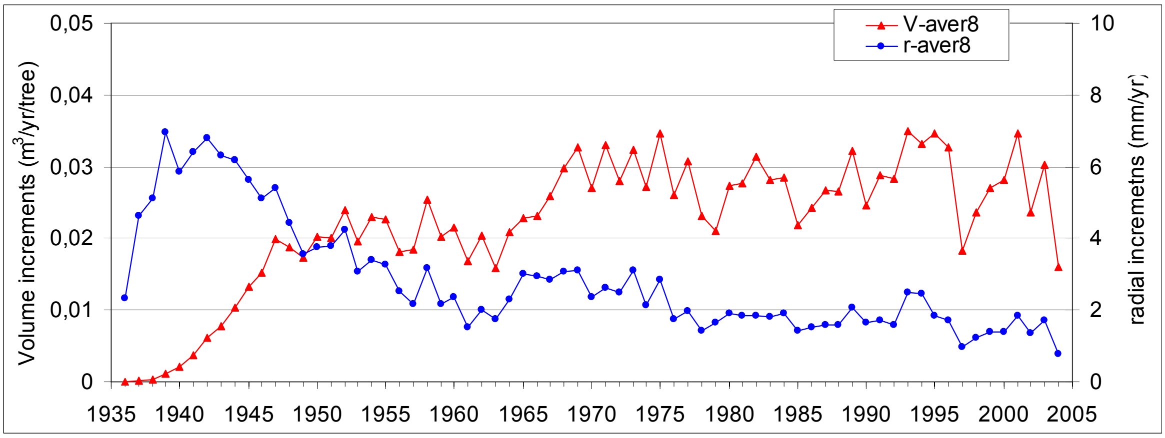


Figure 12 *The comparison of average measured radial increments and average volumes calculated from measured radial increments and measured height increments (69 years).*

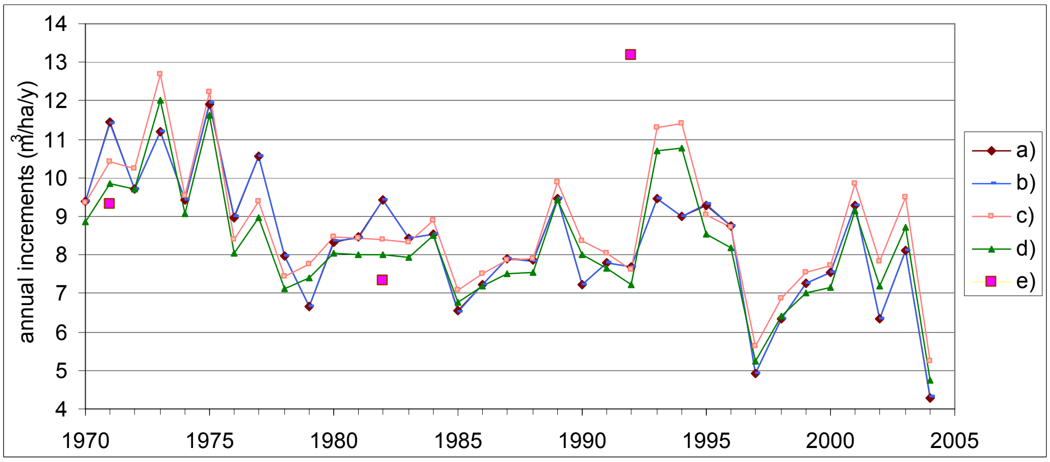


Figure 13 *The comparison of average annual volume increments per ha (m^3/ha/y) in the last 35 years calculated through: a) measured diameters and measured heights, b) measured diameters and modeled heights, c) the Puhek's equation for woody biomass using measured diameters and modeled heights, d) the Puhek's equation for trunk biomass using measured diameters and modeled heights, and e) values noted in the Forest Management Plans.*

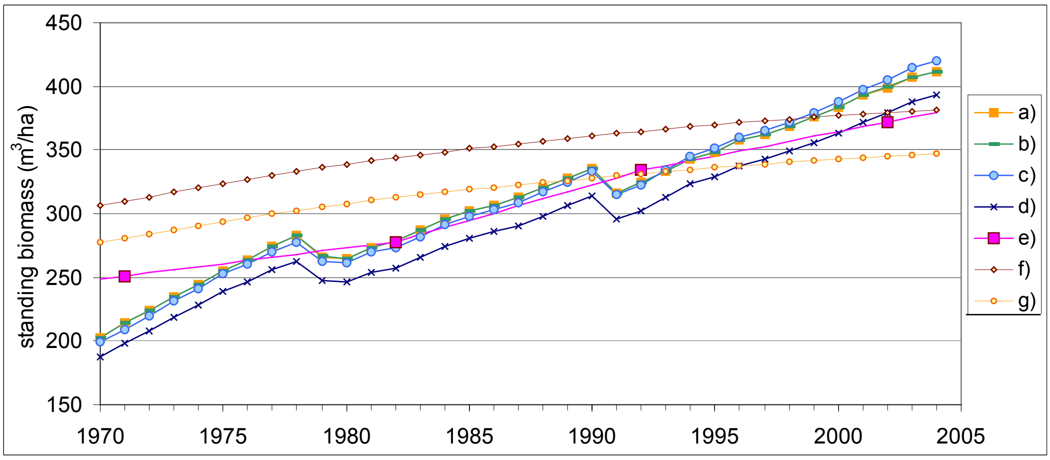


Figure 14 *The comparison of average standing biomass (m^3/ha) in the last 35 years calculated through: a) measured diameters and measured heights, b) measured diameters and modeled heights, c) the Puhek's equation for woody biomass using measured diameters and modeled heights, d) the Puhek's equation for trunk biomass using measured diameters and modeled heights, e) values were noted in Forest Management Plans, and f) values predicted in the Yield Tables for site index 28, and g) for site index 26.*

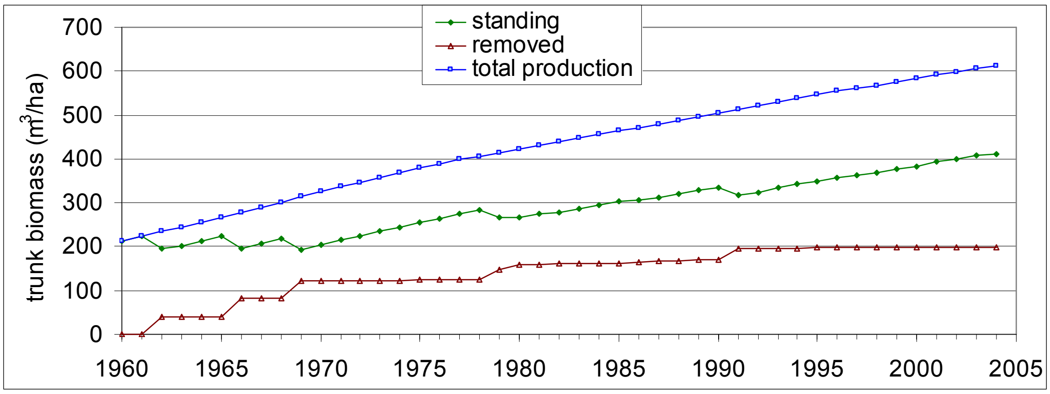


Figure 15 *The comparison of the standing trunk biomass, the cumulative removed trunk biomass, and the sum of standing and cumulative removed volume of wood per stand (m^3/ha).*

To calculate weight of annual increments we used the data on the density of dry black alder wood (Wagenführ, 1996): 450-510-600 kg/m^3.

Accurate annual volume increments in the sand before 1970 could not be determined as the data on the density of trees in the stand in its early ages were not available. Calculations of annual increments were performed through the assumption that the initial density of planting was 3000 plantings per hectare and that the number of trees logarithmically decreased with age. We used logarithms to the base of 90 years. We assumed that the period of 90 years corresponded to the living time of the stand under natural conditions. Under these assumptions we got the highest annual increment of about 18,5 m^3/ha/y between the ages of 12 and 18 years. This was in agreement with the statement of Nemesszeghy (1986) that the highest annual increments of 15 and 20 m^3/ha/y were observed in these stands between the age of 16 and 20 years. The annual increments calculated in this study for 40- to 50-year-old stand (8,95±1,75 m^3/ha/y) were within the range of values of annual increments proposed by Nemesszeghy (1986) (8,3 to 9,3 m^3/ha/y), whereas after the age of 50 years our values (8,4±1,5 m^3/ha/y) surpassed his observations (7,1 to 7,9 m^3/ha/y).

In our stand we determined the average timber volume of 1,5 m^3/tree (vales from 0,98 to 2,13 m^3/tree). These values were in the upper range of the management goals for these stands noted in Nemesszeghy (1986) (1,3 to 1,5 m^3/tree). Also the observed number of trees (350 trees/ha) was at the upper limit of the management goals (300 to 350 trees).

3.1.2 Data on forest management

Among the silvicultural data we considered thinning measures, particularly the amount of wood that was removed in pre-commercial thinning measures. Besides this, we reviewed reports on important events in these stands like the appearance of frosts, long-lasting or exceptional high flooding, diseases, calamities, etc. (Silvicultural Chronicle, 1971-1992). The Silvicultural Chronicle (1971-1992) was a valuable source of data on these events in individual years. The pest damage was not observed in the history whereas the intensity of annual seed production in black alder stands was not recorded.

The silvicultural data for the Forest Management Unit Dolinsko were obtained from the Regional Units Lendava and Murska Sobota. The data were available for the stand 72B (20,23 ha) which included our research site. The data included reports on the annual volume of removed trees (thinnings; Table 3), and the data on the biomass of wood and biomass increments at the beginning of each decade (Figure 13, Figure 14). Volume of wood removed in 1999 and in 2002 was not accounted for in this research, as it refers to the final felling in a part of the stand and it did not affect the environmental conditions in the plot under study.

Thinning measures were always performed during the winter. The research has considered effects of thinning performed before the current growing season (thinning or thinn), before the previous growing season (thinning y-1), two years before the growing season (thinning y-2), and three years before the growing season (thinning y-3).

Table 3 *The volume of wood (m^3/ha/y) removed from the stand 72B in individual years.*

Year	*1973*	*1975*	*1979*	*1980*	*1982*	*1986*	*1987*	*1989*	*1991*	*1995*	*1999*	*2002*	*2004*
V removed	*0,49*	*1,07*	*23,53*	*9,79*	*4,84*	*2,32*	*2,32*	*1,83*	*27,14*	*3,36*	*40,39*	*12,11*	*45,77*

3.1.3 Meteorological data

The meteorological and hydrological data were obtained from the nearest permanent Hydro-Meteorological Station (HMS). As the area is flat the data from the about 7 km distant HMS Lendava were considered to be valid for our stand. Among the meteorological data we investigated monthly data on: the duration of sun radiation (hours), precipitation (mm), evapotranspiration (ET) (mm), the difference between precipitation and ET, number of days with white frost, number of days with snow, maximum, average, and minimum monthly temperatures (ºC), cumulative monthly temperatures above 0ºC, above 5ºC, and above 10ºC, number of days with minimum temperature above 0ºC, below -4ºC, below -10ºC and above 25ºC, as well as number of days with maximum temperature above 10ºC and above 25ºC in individual months. Some values of meteorological parameters in the period under study are presented in the Figure 16.

According to Chmielewski and Rötzer (2001), Antonić et al. (1998/99) and the data from the Environmental Agency of the Republic of Slovenia (ARSO; see Chapter 1.2.3.1) we determined that the growing season extends between April and October (4-10). We investigated the data (attributes) for each month during this period (e.g. July: 7; August: 8, etc.) as well as the data aggregated into groups: averaged or extreme values between April and June (4-6), between May and July (5-7), between July and August (6-8), between May and August (5-8), etc.

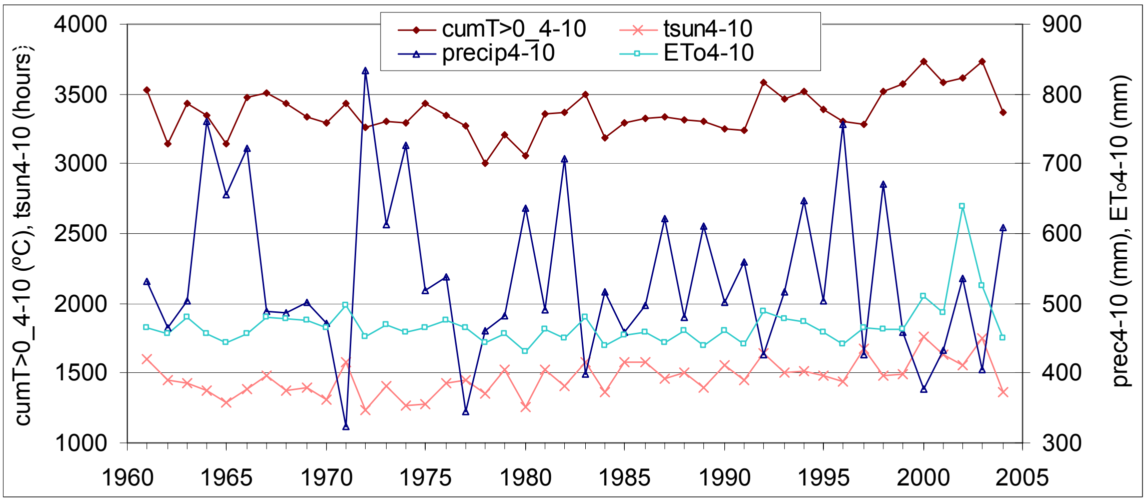


Figure 16 *Values of some meteorological attributes in the period under study: cumulative temperatures above 0ºC (cumT>0_4-10), precipitation (precip4-10; mm), duration of sun radiation (tsun4-10; hours), and reference evapotranspiration (ET_o4-10) during the vegetation period (from April to October; 4-10).*

Special attention was dedicated to the determination of reference (ET_o) and the actual evapotranspiration (ET_a). Actual evapotranspiration is closely connected to the photosynthetic activity and therefore it is also linked to the annual production and the work of the whole ecosystem (Rockström et al., 1999). ET_a from forest canopies is strongly dependent on the received energy, VPD, and on many stand properties (see Chapter 1.2.3.12). It was determined that the rate of water depletion from seven out of ten European forests did not change until 60-75% of the available water in the soil had been exploited (Roberts, 1983).

Several different methods exist to calculate the reference evapotranspiration (ET_o) nowadays (Kuzmin and Vershinin, 1974; Allen et al., 1989). The application of the Penman's equation is the most common and the most reliable (Herbst and Kappen, 1999; Bidlake et al., 1996; Dekker, 2000; Samson, 2001; Kajfež-Bogataj and Kurnik, 2004). This equation was proposed as a standard for ET_o calculation (Jensen et al., 1997) even though it is data demanding. The Penman's equation requires the data on four meteorological attributes: sun radiation, wind speed, minimum and maximum temperature, and relative humidity. ET_o can be calculated for all hourly, daily, or monthly data steps (Allen et al., 1989). After applying an appropriate crop coefficient it can be calculated for hypothetical reference crop in potential conditions, e.i. for standard and well-watered grass or for alfalfa covered surface (Lhomme, 1999; Allen at al., 1998).

Theoretically ET_o could be calculated for forested landscapes as well, if we know appropriate crop coefficient. However, this coefficient varies during the year and from year to year (Gochis and Cuenca, 2000; Verstraeten et al., 2005) and many problems appeared in practice in its determination (Roberts, 1983; Samson, 2001; Vilhar, 2006). Reliable coefficients for different forest canopies are not available yet. Forests differ in age, in stand structure, in the hydraulic conductivity of their leaves and wood, in their physiological reactions to the sun radiation, the VPD and the drought, in their climatic conditions, etc. (Pezeshki and Hinckley, 1988; Breda et al., 1995; Eschenbach, 1995; Zhang et al. 1999; Wilson et al., 2000; Vilhar, 2006). Several different models are used nowadays to calculate ET from forest stands. In general they can be divided into single-layer ("one big leaf") and multilayer approaches (Dekker, 2000; Lebaube et al., 2000; Samson, 2001).

As it was described in the Chapter 1.2.3, black alder develops deep roots, it has very high and sustained evaporation and successful regeneration of water potential even in drought conditions. Consequently we assumed that ET_o is the most reliable estimate of ET_a in these stands. However, we made corrections to account for the reduction of evaporation in very dry conditions. In months in which the groundwater level was below the critical value below the soil surface, we estimated that ET_{oa} was reduced (Table 4). Percentages of reduction were determined according to the knowledge that black alder may loose up to half as much water through the cuticle, with stomata closed, as it does with stomata open (Levitt, 1980; op.cit. Seiler, 1985) and accounting for the values of crop coefficients proposed by Penman (0,6 to 0,8; Brilly and Šraj, 2000). In dry conditions black alder was assumed to constrict its ET_a to levels that are maximal for crop plants in the majority of terrestrial habitats.

Table 4 *ET_{oa} in percentages of ET_o that were assumed to be retained at different levels of drought (levels of the groundwater below the soil surface).*

Groundwater level *(cm below surface)*	***ET_{oa}*** *(in % of ET_o)*
-70	*60%*
-60	*70%*
-50	*80%*
-40	*90%*

3.1.4 Hydrological data

The hydrological data were obtained from the nearest permanent measurement station Čentiba. This station is located at the Ledava River about 10 km downstream from our research stand. Its longitude is 16,478 and its latitude is 46,535. It is 154,67 m above the sea level. Its catchment area is 856,7 km^2. It started its operation in 1970.

Among the hydrological data we acquired the data on the monthly minimum, average, and maximum monthly Ledava River levels, and the corresponding data on the groundwater levels. Our stand lies within the Ledava River's catchment area and the river flows a bit more than one kilometer from the stand. The research of Levanič (1993), performed in the neighboring stand (stand 68A), and the research of Smolej (1995) showed that the groundwater level in this area fluctuates in close interdependence with the Ledava River level. The minimum, average and maximum monthly groundwater levels were measured in an about 7 km distant well. This was the only data set, which was available only for the period of 25 years. These data showed poor agreement with the annual increments (Table 7; Figure 21) and they were not used in the further work. Low regression correlation coefficients most probably indicate that the sampling well was too far away and that it was affected by some other hydrological regimes.

In September 2004 we bored a bit more than one meter deep well to trace the groundwater depth in our research plot. We inserted the perforated tube into the well and we covered it to protect it from precipitation. The data on the groundwater level in this well were recorded four times with the precision of one centimeter. The data on the groundwater level were used to determine the correlation between the groundwater level and the Ledava River level, more precisely to determine the level of the River Ledava at which the ground water begins to overflow the stand surface. In this way the data on the daily Ledava River levels were used to calculate the groundwater levels.

Inflows of groundwater into the stand were calculated as the difference between monthly ET_{oa} and monthly precipitation, taking into account the change of water level between two successive years. The inflows took place when ET_{oa} surpassed the amount of precipitation and when, at the same time, the calculated groundwater level did not change in the same proportion. Outflows of the groundwater, on the other hand, were calculated in such a way that the groundwater (more precisely the Ledava River) maintained the measured levels. They were calculated as a difference between the average water level in the stand in the recent and in the following year (or growing period), taking into account the amount of precipitation and ET_{oa}. All attributes were calculated over the whole year as well as for the data on water flows during the growing season.

The amount of water in the soil was calculated through the known porosity of sandy soil (Kalan et al., 1988; Brilly and Šraj, 2000; Urbančič et al., 2000; Zupanc and Pintar, 2001). Because the data on soil profile were available only until the depth of 130 cm (Kalan et al., 1988) deeper layers were assumed to have the same texture as the soil at 130 cm.

3.2 Data mining

One of the most important questions in ecological modeling today is how to get reliable attributes and how to build ecosystem properties into our models (Jørgensen, 1999). One of the most crucial and the weakest point of modeling is often the estimation of parameters (Jørgensen, 1999). At the same time we meet an increasing availability of computational methods for regression and time-series prediction (Langley et al., 2002).

This work was realized in two subsequent phases. Firstly we performed feature selection by statistical methods. In the second phase data mining algorithms were used to discover sub-models describing the system under study. Among the machine learning methods we applied two different approaches to test their potentials for work with the data under study and to test the adequacy of their results for application in ecological modeling. The first method was used to generate regression and model trees. The second method was used for equation discovery tasks.

The data mining techniques like machine learning were used to search for mathematical correlations between the measured data. In these techniques measured data are used to train a neural network that can then be used to predict future behavior (Džeroski, 2001a and 2002). A common view in machine learning is that machine learning algorithms perform a search though a space of hypotheses (patterns) that explain (are valid in) the data at hand (Džeroski, 2001b). Applications range from data mining programs that discover general rules in large data sets, to information filtering that automatically learn users' interests (Langley et al., 2002). Machine learning methods applicable to modeling can result in models with the form of classification or regression trees, or rules (Džeroski et al., 1999).

3.2.1 Feature selection

Stand characterization, management data, meteorological and hydrological data altogether resulted in 333 different attributes, which were tested for their effects on annual increments. To reduce the number of attributes and to select the most appropriate dependent variable we applied linear regression and we determined the regression correlation coefficient (R^2). The regression correlation coefficient (R^2) is a measure of the proportion of variability explained by or due to the regression (linear relationship) in a sample of paired data. It is a number between zero and one. A value close to zero implies a poor model. The STATISTICA 6.0 software was used in this part of study.

We searched for regressions between average annual increments of eight trees and individual environmental and management attributes. Radial, vertical and volume increments were tested. Vertical and volume increments showed considerably lower correlations with the environmental and management data than radial incremetns and they were consequently not used in the subsequent analyses. During the analyses we considered the significance level P=0,05.

3.2.2 Model trees and regression trees

In our work we applied model and regression trees. Regression trees predict the numeric value of the continuous dependent variable (class) or linear function of some attributes from the values of a set of independent variables (attributes), which may be either continuous or discrete. M5' algorithm maximizes the expected error reduction when splitting the remaining learning examples into several sets depending on the various potential tests (Kubat et al., 1997; Džeroski, 2001b).

A regression tree has a rule in each inner node that tests the value of a certain attribute. In each leaf there is a model for predicting the class. The model can be a linear equation or a constant. Trees having linear equations in their leaves are also called model trees (Zmazek et al., 2003).

Tree construction proceeds recursively, starting with the entire set of training examples (entire table). At each step the most discriminating attribute is selected as the root of the subtree and the current training set is split into subsets according to the values of the selected attribute (Zmazek et al., 2003). Technically speaking the most discriminating discrete attribute or continuous attribute test is the one that the most reduces the variance of the values of the class variable. For continuous attributes a threshold is selected and two branches are created based on that threshold. For the subsets of training examples in each branch the tree construction algorithm is called recursively. The tree construction stops when the variance of the class values of all examples in a node is small enough or if some other stopping criterion is satisfied. These nodes are called leaves and are labeled with a model (constant value or linear equation) for predicting the class value. The tree is pruned to prevent trees from over-fitting the data (Zmazek et al., 2003).

3.2.2.1 Trees construction

Model and regression trees were determined using a collection of machine learning algorithms for data mining tasks WEKA. WEKA is an open source software issued under the GNU General Public License. Its machine learning algorithms are written in Java programming language. It provides a variety of tools for data preprocessing, classification, regression, clustering, association rules, and evaluating the result of learning algorithms on any given dataset. The advantages of WEKA are high explanatory power and clearness of results. It has often proved its usefulness in explanations of relationships in environmental data (Zmazek et al., 2003; Frank et al., 2004).

In this research M5' algorithm was used. This algorithm is one of the most widely used regression tree systems (Zmazek et al., 2003).

The research was conducted on continuous attributes and class values. As the input data we had a worksheet with numerous attributes and annual increments of individual trees as classes. The WEKA's ability to work with numerous different attributes enabled fast and reliable work, as we did not have to previously vigorously reduce the number of attributes. Firstly we run M5' on 164 attributes with different degrees of pruning. After that we made further selection and we run eight different combinations (analyses) of attributes ranging from 15 to 55 attributes (Table 5). For each of the attributes the data on 35 years and 8 trees were available, which together resulted in a training set of 280 instances.

Each analysis was run under several different restrictions about the extent of pruning (M = 5, 15, 20, 33, 50 and 100, in some cases also M = 40, 45, 55 and 60). Altogether 80 model trees and 80 corresponding regression trees were constructed. The models with the best measure values were further studied.

***Table 5** Attributes that took place in individual experiments in WEKA.*

Analysis 1	**Analysis 2**	**Analysis 3**	**Analysis4**	**Analysis 5**	**Analysis 6**	**JLanaliza 7**	**JLanaliza 8**
Attributes: 55	Attributes: 15	Attributes: 26	Attributes: 19	Attributes: 45	Attributes: 28	Attributes: 46	Attributes: 25
age	*age*	*age*	*age*	*age*	*age*	*age*	*age*
thinn	*thinn*	*thinn*	*thinn*	*thinn*	*thinn*	*thinn*	*thinn*
thinn_y-1	*thinn_y-1*	*thinn_y-1*	*thinn_y-1*	*thinn_y-1*	*thinn_y-1*	*thinn_y-1*	*thinn_y-1*
thinn_y-2	*thinn_y-2*	*thinn_y-2*	*thinn_y-2*	*thinn_y-2*	*thinn_y-2*	*thinn_y-2*	*thinn_y-2*
thinn_y-3	*thinn_y-3*	*thinn_y-3*	*thinn_y-3*	*thinn_y-3*	*minL5*	*maxL5*	*maxL5*
maxL5	*maxL5*	*maxgw12-3*	*maxL6*	*magw7*	*minL7*	*maxL5-7*	*minL4*
maxL6	*maxL8*	*maxL6*	*minL4-10*	*avergw7*	*minL9*	*maxL5-9*	*minL5*
maxL7	*maxL5-7*	*minL4-7*	*minL5-7*	*minL5*	*minL4-7*	*minL4*	*minL4-7*
maxL8	*minL8*	*minL4-10*	*minL5-8*	*minL6*	*minL8-10*	*minL5*	*minL4-10*
maxL4-7	*minL5-9*	*minL5-7*	*minL5-9*	*minL7*	*minL4-10*	*minL7*	*minL5-7*
maxL4-10	*tsun4-9*	*minL5-8*	*minL12-3*	*minL8*	*minL4-6*	*minL8*	*minL5-8*
maxL5-7	*minT4-10*	*minL5-9*	*averL4-10*	*minL9*	*minL5-7*	*minL9*	*minL4-9*
maxL5-8	*averT7*	*minL4-9*	*tsun4-6*	*minL4-7*	*minL5-8*	*minL4-7*	*minL12-3*
maxL4-9	*d-snow_w-1*	*minL12-3*	*tsun5-9*	*minL8-10*	*minL5-9*	*minL8-10*	*averL5*
minL4	*r-tree*	*averL4-10*	*tsun4-9*	*minL4-10*	*minL4-9*	*minL4-10*	*averL4-6*
minL5		*tsun4-7*	*precip7*	*minL4-6*	*averL4-10*	*minL4-6*	*averL5-7*
minL6		*tsun4-6*	*maxT6*	*minL5-7*	*averL4-6*	*minL5-7*	*tsun4-9*
minL7		*tsun5-9*	*d-snow_w-1*	*minL5-8*	*averL5-9*	*minL5-8*	*precip7*
minL8		*tsun4-9*	*r-tree*	*minL5-9*	*averL4-9*	*minL5-9*	*prec-ET_o8-10*
minL4-7		*precip7*		*minL4-9*	*tsun4*	*minL4-9*	*maxT7*
minL4-10		*prec-ET_o7*		*averL6*	*tsun4-7*	*minL12-3*	*minT4*
minL5-7		*maxT6*		*averL4-7*	*tsun4-6*	*averL5*	*d-minT<0_4*
minL5-8		*averT10*		*averL4-10*	*tsun5-9*	*averL7*	*dwf_4-7*
minL4-9		*dwf_4-7*		*averL4-6*	*tsun4-9*	*averL4-7*	*d-snow_w-1*
tsun4		*d-snow_w-1*		*averL5-8*	*dwf_5*	*averL4-6*	*r-tree*
tsun5		*r-tree*		*averL5-9*	*dwf_4-7*	*averL5-7*	
tsun6				*averL4-9*	*d-snow_w-1*	*averL5-8*	
tsun4-7				*tsun4*	*r-tree*	*averL5-9*	
tsun4-10				*tsun6*		*averL4-9*	
tsun4-6				*tsun4-7*		*tsun4*	
tsun5-7				*tsun4-10*		*tsun9*	
tsun5-8				*tsun4-6*		*tsun4-10*	
tsun4-9				*tsun5-8*		*tsun4-6*	
precip7				*tsun5-9*		*tsun5-9*	
precip8				*tsun4-9*		*tsun4-9*	
precip4-7				*precip7*		*precip7*	
precip4-10				*prec-ET_o7*		*precip8*	
prec6-8				*maxT6*		*precip8-10*	
prec5-8				*averT10*		*prec-ET_o7*	
prec4-9				*cumT>0_10*		*prec-ET_o8-10*	
prec-ET_o7				*dwf_4*		*maxT7*	
prec-ET_o8				*dwf_5*		*minT4*	
prec-ET_o4-7				*d-snow_w-1*		*d-minT<0_4*	
prec-ET_o4-10				*r-tree*		*dwf_4-7*	
prec-ET_o4-6						*d-snow_w-1*	
prec-ET_o5-7						*r-tree*	
prec-ET_o6-8							
prec-ET_o5-8							
prec-ET_o4-9							
minT4							
cumT>0_4							
cumT>0_5							
dwf_4-7							
d-snow_w-1							
r-tree							

- *w-1: previous winter*
- *Each analysis was based on 280 instances.*

The numbers mean the month(s) of the year the attribute refers to, e.g. 12-2 refers to the period between December of the previous year and the February of the current year; 4-7 refers to the period between the current April and July. Max, aver and min refer to the minimum, average and maximum values respectively; thinn: thinning (m^3/stand) at the beginning of the current season, before the previous growing season (thinn y-1) and two years before the current growing season (thinn y-2); gw: groundwater; L: the Ledava River level; tsun: the duration of sun radiation (hours); prec: precipitation (mm); ET_o: potential evapotranspiration (mm); prec-ET_o: the difference between precipitation and potential evapotranspiration (mm); T: temperature; cumT>0: cumulative temperature above 0ºC in this period; d-minT<0: number of days with minimum temperature below 0ºC; dwf: number of days with white frost; d-snow_w-1: number of days with snow in the winter before the current growing season, r-tree: radial increments of individual trees (dependent variable).

The most common measures of fit in WEKA are noted in the Table 6. In the model evaluation and model selection we focused on the model structure, correlation coefficients and RRSE as they were calculated through a standard 10-times cross-validation method.

Table 6 *The most common measures in WEKA.*

Abbreviation	*Name*	*Formula*
T_{corr}	*Correlation coefficient*	$R = \sigma_{xy}/\sigma_x\sigma_y$
MSE	*Mean Square Error*	$((p_1-a_1)^2+....+(p_n-a_n)^2)/n$
RMSE	*Root Mean Square Error*	$(((p_1-a_1)^2+....+(p_n-a_n)^2)/n)^{1/2}$
MAE	*Mean Absolute Error*	$((p_1-a_1)+....+(p_n-a_n))/n$
RSE	*Relative Squared Error*	$((p_1-a_1)^2+....+(p_n-a_n)^2)/((\bar{a}-a_1)+ ....+(\bar{a}-a_n))$
RAE	*Relative Absolute Error*	$(\lvert p_1-a_1\rvert+....+\lvert p_n-a_n\rvert)/(\lvert\bar{a}-a_1\rvert+....+\lvert\bar{a}-a_n\rvert)$
RRSE	*Root Relative Squared Error*	$((p_1-a_1)^2+....+(p_n-a_n)^2)/((\bar{a}-a_1)+ ....+(\bar{a}-a_n))^{1/2}$

T_{corr}: The correlation coefficient. It expresses the level of correlation between the measured and predicted values.
MSE: The average of the squared differences between each computed value (p_i) and its corresponding correct value (a_i). It is one of the most commonly used measures of success for numeric prediction.
RMSE: The square root of the mean-squared-error. The RMSE gives the error value the same dimensionality as the actual and predicted values. It measures the discrepancy between measured and predicted values. Smaller RMSE values indicate lower discrepancies.
MAE: The average of the difference between predicted and actual value in all test cases; it is the average prediction error.
RSE: The total squared error made relative to what the error would be if the prediction was the average of the absolute value.
RAE: The total absolute error made relative to what the error would be if the prediction was simply the average of the actual values.
RRSE: The square root of the RSE is taken to give it the same dimensions as the predicted values themselves.

3.2.3 Equation discovery

Due to the disadvantages of regression trees and model trees including their linearity, the disability to work with combined (multiplied) attributes, and the discontinuance of the results between individual leaves, we decided to apply another machine learning tool.

The systems for differential equations discovery proved to be the most useful in ecological modeling, as differential equations are the prevailing formalism used in ecological modeling (Džeroski et al., 1999). Differential equations describe the change of state of dynamic systems over time. The system of differential equation discovery help human experts to discover natural laws in collections of measured data, and to express them in the form of equations (Džeroski et al., 1999).

The machine learning algorithm CIPER was applied to identify the most important attributes affecting annual growth and to find the relationships between the annual radial increments and the environmental and management attributes.

3.2.3.1 CIPER

CIPER stands for the Constrained Induction of Polynomial Equations for Regression (Pečkov et al., 2006). It is a recently developed algorithm for inducing polynomial equations (Todorovski et al., 2004). The algorithm heuristically searches through the space of possible equations for solutions that satisfy the given constraints. The output of the CIPER is a polynomial equation that satisfies the complexity constraints and fit the data best (Pečkov et al., 2006).

In the space of polynomials of arbitrary degree, we can always find a polynomial with error zero on the training data. However, such equations can be very complex. To find an optimal trade-off between complexity of the model and well fitting the data the CIPER uses Minimum Description Length principle (MDL). The MDL principle is a method for inductive inference that provides a generic solution to the model selection problem (Pečkov et al., 2006).

In the CIPER the number of attributes that can be considered at the same time is limited and it is connected with the number of initial data we have (in our case the number of trees and the number of years). Consequently we firstly had to reduce the dataset under research, as it was described in the Chapter 3.2.1.

The feature selection based on the statistical methods resulted in an important reduction in the number of attributes. 84 resulting attributes are noted in the Table 7. With these attributes we made 52 different combinations of attributes. Due to the relatively low number of available data for each attribute (35 years times 8 trees) we tried to avoid combinations of more than 6 to 10 attributes. Each combination of attributes was run under different constrictions about the complexity of the model. Altogether 124 experiments were run. Further selection of models was performed according to the error measures, complexity, and reasonableness of generated equations. The results of each model were considered when choosing attribute combinations for the next experiment.

Table 7 *Selected attributes for the CIPER and corresponding regression correlation coefficients (in brackets).*

age (-0,619)	*maxL_5-7 (0,200)*	*averL_12-2 (0,422)*	*ET_o_4-10 (-0,072)*
thinn (-0,398)	*maxL_5-9 (0,192)*	*tsun_4 (-0,362)*	*maxT_6 (-0,297)*
thinn_y-1 (-0,149)	*minL_4 (-0,533)*	*tsun_4-7 (-0,392)*	*maxT_7 (-0,031)*
thinn_y-2 (0,075)	*minL_5 (-0,609)*	*tsun_4-10 (-0,383)*	*maxT_4-10 (-0,073)*
maxgw_7 (0,205)	*minL_7 (-0,613)*	*tsun_4-6 (-0,414)*	*maxT_5-7 (0,130)*
maxgw_4-7 (0,062)	*minL_8 (-0,582)*	*tsun_5-9 (-0,417)*	*maxT_12-2 (0,049)*
maxgw_8-10 (0,016)	*minL_9 (-0,641)*	*tsun_4-9 (-0,439)*	*minT_4 (0,066)*
maxgw_4-10 (0,055)	*minL_4-7 (-0,665)*	*precip_7 (-0,233)*	*minT_8 (-0,126)*
mingw_7 (0,177)	*minL_8-10 (-0,645)*	*precip_8 (0,114)*	*minT_4-7 (0,066)*
mingw_4-7 (0,082)	*minL_4-10 (-0,684)*	*precip_4-7 (0,155)*	*minT_4-10 (-0,118)*
mingw_8-10 (0,046)	*minL_4-6 (-0,627)*	*precip_8-10 (0,085)*	*minT_4-6 (0,066)*
mingw_4-10 (0,062)	*minL_5-7 (-0,683)*	*precip_4-10 (0,166)*	*minT_4-9 (0,066)*
avergw_7 (0,194)	*minL_5-8 (-0,690)*	*precip_4-9 (0,182)*	*averT_4-7 (-0,020)*
avergw_4-7 (0,064)	*minL_4-9 (-0,668)*	*prec-ET_o_7 (0,226)*	*averT_4-10 (-0,078)*
avergw_8-10 (0,017)	*minL_12-2 (-0,548)*	*prec-ET_o_8 (0,120)*	*cumT>0_4-7 (-0,005)*
avergw_4-10 (0,026)	*averL_5 (-0,553)*	*prec-ET_o_4-7 (0,155)*	*cumT>0_4-10 (-0,073)*
maxL_5 (-0,282)	*averL_4-7 (-0,600)*	*prec-ET_o_8-10 (0,092)*	*d-minT<0_4-7 (-0,198)*
maxL_7 (-0,086)	*averL_8-10 (-0,553)*	*prec-ET_o_4-10 (0,162)*	*d-minT>25_6 (-0,147)*
maxL_4-7 (-0,092)	*averL_4-10 (-0,658)*	*prec-ET_o_4-9 (0,177)*	*dwf_4-7 (-0,399)*
maxL_8-10 (-0,150)	*averL_4-6 (-0,613)*	*ET_o_4-7 (-0,054)*	*dwf_4-10 (-0,130)*
maxL_4-10 (-0,058)	*averL_4-9 (-0,635)*	*ET_o_8-10 (-0,103)*	*d-snow_w-1 (0,141)*

Numbers refer to the month(s) of the year the attribute refers to. e.g. 12-2 refers to the period between December of the previous year and the February of the current year; 4-7 refers to the period between current April and July; max, aver and min refer to the minimum, average and maximum values respectively; thinn: thinning (m^3/stand) in the beginning of the current season, before the previous growing season (thinn y-1) and two years before the current growing season (thinn y-2); gw: groundwater level; L: the Ledava River level; tsun: duration of sun radiation (hours); prec: precipitation (mm); ET_o: potential evapotranspiration (mm); prec-ET_o: the difference between precipitation and potential evapotranspiration (mm); T: temperature; cumT>0: cumulative temperature above 0ºC in this period; d-minT<0: number of days with minimum temperature below 0ºC; d-minT>25: number of days with minimum daily temperature above 25ºC; dwf: number of days with white frost; d-snow_w-1: number of days with snow in the winter during the current growing season.

Among error measures calculated in CIPER we focused on (for explanation see Table 6):

- Average Root Square Error
- RAE
- RRSE

Regression correlation coefficients were not studied as they are not calculated in CIPER.

3.3 Emergy synthesis

This chapter presents basic principles of emergy accounting and the data on emergy synthesis of the system under study over a period of 35 years. Flows, storages and performance indicators were calculated for each individual year.

Emergy synthesis was performed through the following methodological steps:

- A system diagram of the system under study was constructed.
- A resource evaluation table was set up.
- Emergy indices were calculated.
- A computer model of the system under study was constructed. Model behavior was compared to the data in the emergy evaluation table.
- Sensitivity analyses and simulations were performed and the results were explained.

3.3.1 Description of emergy systems evaluation

Emergy is the available energy of one kind previously used up directly and indirectly to make a product or service (Odum, 1996). Each form of contributing flow is expressed in units of solar energy that would be required to generate it. Energies of different kinds are multiplied by the appropriate Unit

Emergy Values (UEVs) or "emergy intensity", to convert these energy qualities into a single energy quality numeraire.

The former term transformity was adviced to be replaced by the term Unit Emergy Value (UEV) to describe the general class of ratios used to describe the amount of emergy required per unit of measure (Brown and Ulgiati, 2004; Odum, 2000c; Odum et al., 2000a). This term includes (Brown, 2005), among others:

- Transformity: emergy per unit of available energy (sej/J) (exergy).
- Specific emergy: unit emergy value of matter defined as the emergy per mass. It is usually expressed in solar emergy per gram (sej/g). Solids are usually evaluated through the data on emergy per mass for its concentration.
- Emprice: unit emergy value used to convert money payment (human work invested) into emergy units. It is expressed as sej/$, sej/€, etc.

The energy of solar radiation as the most dispersed energy in the world is assumed to have UEV of one. The energy of sun, together with other environmental sources, contributes to the production of plant tissues. Plant tissues have therefore larger UEV than environmental sources. Items are further concentrated in the animal tissues and are then dispersed through raw materials released by consumers. A similar process is going on in human-driven production systems. Each successive processing stage delivers some "added value" to the product or process. The emergy flow in such energy-chain is the same for all pathways, whereas energy flow decreases in each step (Odum, 1996; Brown et al., 2000). The consequence is a higher UEV of items that need higher emergy inflows and longer turnover time. Consequently the UEV is a measure of energy hierarchy and it is apparently applicable to all quantities of matter, energy, or information. Items with higher UEVs have higher influence on energy flows in a system and longer cycle time, i.e. they are higher in the system hierarchy.

Lower UEVs of items that share the same position in the energy hierarchy is an indicator of higher development and higher degree of sustainability as the product was made in a process that was further developed to construct a product with lower emergy investments. UEV also increases as the product becomes more refined, and it thus can be a measure of maturity and efficiency. For example, the biomass of an old growth natural forest is expected to have higher UEV than younger forests, since its emergy was accumulating for a longer time (Bardi, 2002).

UEVs of inputs are often calculated for systems on a larger basis, whereas UEVs of outputs are always calculated for the system under study. There is no single UEV for the majority of products, but a range. There is probably a lower limit, below which the product cannot be made. Average UEVs are used whenever the exact origin of a resource or commodity is not known or when it is not calculated separately (Brown and Ulgiati, 1999). The emergy of stored resources accounts for the formation time, as it is calculated by multiplying the global emergy budget by their replacement time (Odum, 1996).

Odum (1996) calculated the amount of emergy received by Earth per year (global baseline) of 9,44E+24 sej/y. Newer calculations proposed values of 9,24E+24 sej/y or 15,83E+24 sej/y (Odum, 2000c; Campbell et al., 2005a,b). These calculations were based on different assumptions about reciprocal dependence of environmental driving forces. The choice of a baseline is somewhat "arbitrary", i.e. dependent on assumptions, and in the model we can simply do this by multiplying UEVs by a conversion factor (Odum, 2000c; Campbell et al., 2005 a,b). This approach enabled easy and fast comparison to the previous results. If we use alternative baselines care must be taken to respect the differences in the calculation different baselines (Campbell, 2000; Campbell et al., 2005a). In this study emergy flows calculated based on the planetary baseline 9,44 E+24 sej/y (Odum, 1996) were used.

Global flows like emergy of solar radiation, emergy of precipitation, emergy of evapotranspiration and emergy of wind, are all driven by the same emergy flows. The whole amount of emergy received by the Earth is needed to drive each of them. To avoid double counting only the largest among them is accounted for. A similar rule is valid whenever a process generates two products. Each of them receives the whole emergy needed for the production. If both of them are needed for some process later in the energy hierarchy, only the emergy of the largest flow is accounted for (Odum, 1996). The same rule determines that the emergy of feedback flows cannot be added to the production process whereas the material is (Odum, 1996; Brown and Buranakarn, 2000 and 2003; Buranakarn, 2003;

Cohen, 2003; Odum, 2003; Cohen et al., 2005). This rule is valid in all cases, except for emergy storages that were accumulated in a different time period or in different area. By accounting only for the highest among flows we obtain conservative estimates of the emergy base for that area (Campbell et al., 2005a).

In a coproduct branching the flow in each branch is of a different kind and has different UEV, but both flows carry the same emergy. Instead, when a pathway splits into two flows of the same kind, carrying different mass or energy, emergy splits accordingly so that the same UEV is calculated for the two branches. The question of splits and coproduct branching is further discussed in Odum (1996), Brown and Herendeen (1996), Giannatoni (2003), Collins (2003), and in Odum and Collins (2003).

In a human economy money is paid only to people and never to the environment for its work. In contrast emergy synthesis accounts both for the emergy needed to support production process and for human standard of living. In the absence of better approximation we represent the average value of human service through the emergy-to-money ratio for the economy (Brown and McClanahan, 1996; Odum, 2000b; Tilley and Swank, 2003; Campbell, 2005). This value varies greatly between nations, according to the standard of living and it generally decreases each year as a result of inflation. This ratio is obtained by dividing emergy flow consumed in a state to money in the national economy (gross economic product). This ratio is usually expressed in US dollars (emdollars). At the same time this ratio allows us to expresses any contribution of nature in terms of monetary equivalents to estimate their contribution to the economy. However, these values cannot be mixed with commercial prices.

In principle emergy takes information (DNA, seeds, expertise, hierarchical position, etc) into account as well. It regards emergy as a measure of new information and copies. Emergy of new information is large as it considers the emergy needed to make selections based on testing. If there is only one copy of information in existence, it carries all the solar emergy needed for its development. Although the emergy of one copy can be small, the UEV of a unique copy is large. People increase the UEV of their work through their education and experience, as well as with the amount of emergy consumed per person (Odum, 1988 and 1996). The UEV of the living creature depends on its hierarchical position and importance in the ecosystem as well as on its rarity. In our work we did not focus on emergy of information and biodiversity. The first reason for this decision was the low species diversity of tree species in the stand under study and the second was the deficiency of the data on the overall species diversity in these stands.

3.3.2 System diagrams

Emergy synthesis starts with building a system diagram of the system under study. System diagrams are used to clarify and to explain our understanding of the system under study (Odum, 1995a and 1996). In this representation we show which are driving energies, components in the system and connections among them, yield(s), and borders of the system under study. Among the driving sources we usually account for environmental sources (sun, wind, precipitation, tide, rivers, geological processes, etc.), economically derived sources (fuel, machinery, electricity, food etc.) together with services needed for their production, human labor, monetary exchanges and information flows. Besides, it was used as a conceptual diagram for computer model development in our case.

Items are located from left to right according to their UEV. In this way the emergy of sun is located on the left and the emergy of information and human services lies on the right. In the last step we mark the processes that drive the system and these that take place within the system (flows, relationships, interactions, etc.). Usually quite a complex system diagram is built at the beginning and it is later aggregated to reduce the complexity.

In the systems diagram all output flows that still have available emergy (concentrated material, energy or information) must be marked. Energy that lost its ability to do work (heat) is the only flow that exits at the bottom of the system diagram and it converges to a heat sink at the bottom. All other outflows or products that still carry useful energy exits elsewhere, usually at the right. In a system diagram all inflowing energies and materials must have either storage in the system or an identified outflow.

Feedback and feed-forward flows are very important in ecosystems. Such flows (information, controls, etc.) are fed back from right to left in a diagram and they represent a loss of concentration because of a divergence. As it was described previously, their emergy cannot be added to the emergy needed for a process as this would violate one of important rules in emergy: the emergy of inflows should always equal the emergy of outflows (Odum, 1996).

Symbols used in system diagrams were determined by Odum (1996) and are presented in the Appendix D . Flows of materials, emergy and information are represented by lines, whereas monetary transactions are identified by dashed lines. Monetary transactions flow in the opposite direction than the emergy flows. An interaction of two different energies takes place in monetary exchange, which is represented by an interaction symbol.

In our case the system was limited to the area of one hectare and to the height of the highest tree. In the soil the limit was at the depth of 4 m. This value was determined according to the maximum reported depth of black alder roots (3,8 m; Köstler et al., 1968, op. cit. Stone and Kalisz, 1991; Middelhoff, 2000). Inflows, production processes, storages, outflows, and connections among elements are shown in the Figure 17. In agreement with the availability of meteorological, hydrological and management data, the length of the period under study was limited to 35 years.

The length of the production cycle was 69 years. In the study we accounted for emergy flows before 1970 as well. Due to the lack of reliable data we used average measured meteorological and hydrological values for this period. Management measures were estimated according to the existing norms (Decree on the determination of normative for work in forests, 1999) and on the existing data on management in this period (Kolenko, personal communication, 2004; Forest Management Plans, 1992-2001).

In the present study we did not account for changes in the standard of living and changes in the methodology of tree felling. Our goal was to estimate the process of silviculture in these forests, as it is going on nowadays.

A detailed description of the system under study is given in the next chapter, along with the description of the calculation procedure used in the emergy synthesis.

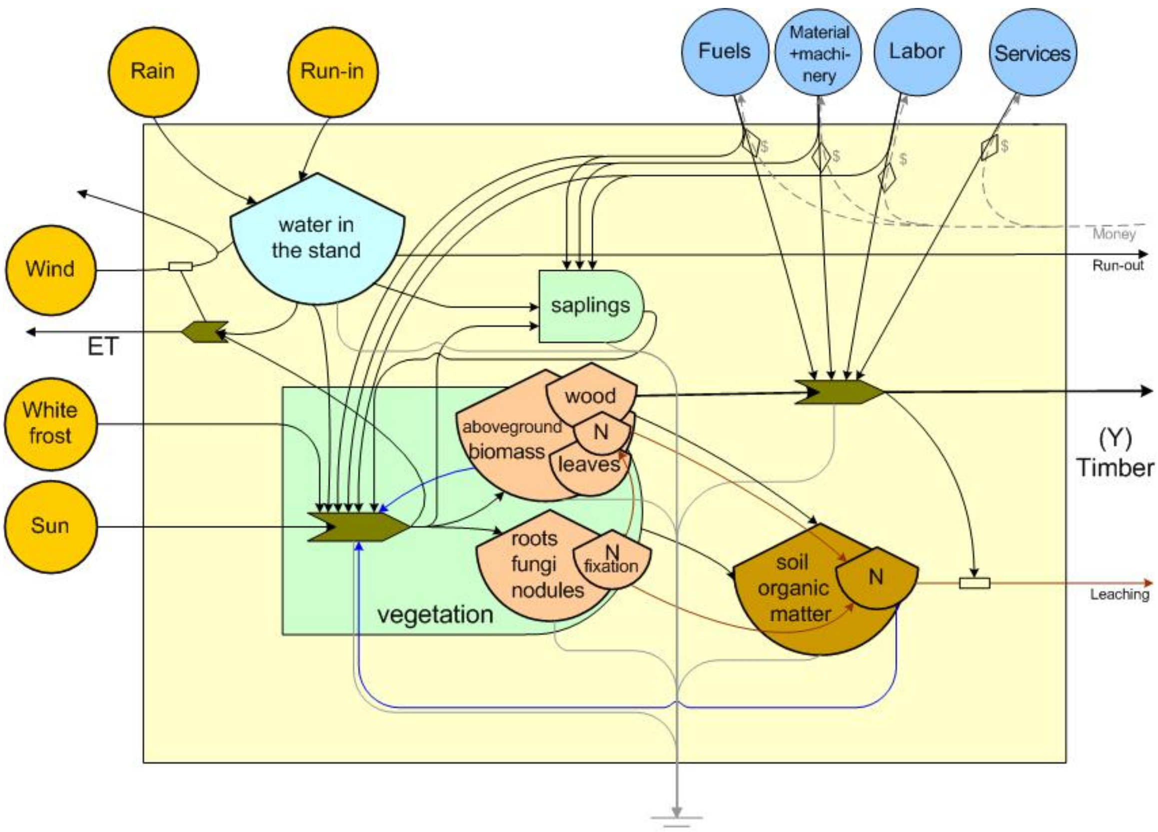


Figure 17 *System diagram of black alder stand in Polana.*

Our model included also nitrogen flows, which have several unique patterns in the system under study. In the majority of ecosystems nitrogen and phosphorus are considered as limiting nutrients. In emergy accounting the entire incoming emergy is needed to drive very important cycles of nutrients (Odum, 1996) and consequently this cycle is a coproduct of the biomass production cycle (Tilley, 1999; Genoni et al., 2003). The overview on global nitrogen cycle and its importance was stressed in the article of Campbell (2003a). He calculated a specific emergy of nitrogen storages from the data on emergy received by Earth per year, from the turnover time of storage and the mass of storage.

3.3.3 Emergy evaluation tables

Each emergy flow that crosses the border of the system diagram is represented as a line item in the emergy table. Emergy evaluation table helps us to represent the energy (or material, information) flows, UEVs used and adequate emergy flows in an ordered way. The way we calculated energy (material, energy) flows and the source of the data is usually explained in the footnotes to the emergy evaluation table.

A common emergy evaluation table consists of five columns:
1) A line item number that identifies the footnote at the end of the table.
2) The name of the item that is evaluated. This item should appear in the system diagram as well.
3) Flows or storages in physical units (joules, grams or dollars). These data are usually given per unit of area (or volume) or per unit of output.
4) A list of UEVs per unit for each line item. These values are usually obtained from previous, independent studies or derived from evaluations in the same study. Calculations are commonly shown in footnotes to the table.
5) Solar emergy of the resource inputs, products or storages. They are calculated as a product of columns 3) and 4). They are measured in emergy per unit time for flows (sej/ha/y), emergy per unit output (sej/ton, sej/MWh, etc.), or in emergy per unit area or volume for storages (sej/ha, sej/ton).

In our study it was not possible to construct a separate table for each individual year. Consequently we decided to construct four tables. In the first table we showed flows and storages in physical units (corresponding to the column 3), in the second table we presented adequate UEVs (corresponding to the column 4), in the third we calculated emergy flows (corresponding to the column 5), and in the fourth table we showed summary flows and emergy indices.

Flows in each table were grouped by types, which are important in the calculation of emergy indices:
- I: environmental sources. They are further divided into renewable driving sources (R) and non-renewable sources from within the system (N).
- F_i: purchased inputs associated with each process step. This flow can be further divided into purchased materials and fuels (M) and human work and services (S).
- Q_i: stored quantities for each transformation step.
- Y_i: yields of outputs for each transformation step.

Whereas relatively low purchased inputs were needed for care and intermediate thinning measures, additional purchased inputs were invested to cut the fallen wood into pieces and to remove them from the stand. For purchased inputs, yields, and performance indices two values were considered: values calculated for produced wood were marked with the number one (e.g. F_1, Y_1, etc.), whereas values calculated for wood cut into pieces and removed from the stand were marked with number 2 (e.g. F_2, Y_2, etc.). Emergy needed for transportation from the stand was not calculated as it depends on the distance of transportation. The produced biomass included both biomass that was in the stand in the individual year and the cumulative amount of wood that was removed from the stand until this year.

Precipitation, run-in, evapotranspiration, and run-out govern water conditions in the stand. Water conditions, together with energy of sun radiation and emergy of purchased inputs (fuels, materials, machinery, labor and services), drive forest growth. Purchased emergy is invested to accelerate forest development phases, to increase annual production, and to maximize benefit in managed ecosystems. Pesticides and mineral fertilizers were not added in the studied case. The conditions that most importantly affected annual increments were also important for the nitrogen fixation process. The nitrogen fixation is related to the photosynthesis intensity and on the availability of photosynthates (Wheeler, 1971; Gordon and Wheeler, 1978; Dawson and Gordon, 1979; Hurd et al., 2001; Gökkaya et al., 2004). Inflow of N_2 to the system was not marked in the systems diagram, as N_2 is the most oxidized form of nitrogen and consequently its UEV is zero by definition. The nitrogen fixation drives toward nitrogen enrichment of the stand. Some nitrogen is leached from the stand during winter precipitation and during heavy rainfall.

3.3.4 Emergy of flows, processes and storages

3.3.4.1 Driving inflows of emergy

Meteorological, hydrological and management data used in the calculation are described in Chapters 3.1.2, 3.1.3, and 3.1.4. The received energy of sun radiation was calculated from the data on duration of sun radiation, taking into account average energy of received sun energy in Murska Sobota and the average duration of sun radiation (the data from ARSO). Global average UEVs (Odum, 1996) were used for the majority of driving flows including sun radiation, wind, precipitation and evapotranspiration, purchased material, fuel and human labor. The UEV of run-out was calculated as UEV of rain, multiplied by the ratio between annual precipitation and average annual run-off from the stand. The same rationale was used to calculate UEV of run-in, with the exception that average values were used over the whole studied period (35 years). In the present emergy synthesis we applied the data on average amounts of water inflows because UEVs of run-in would be the highest in years in which run-out from the stand was negligible (ET_{oa} exceeded the amount of precipitation).

In agreement with the emergy methodology only the largest emergy flow among precipitation, wind, solar insulation, evapotranspiration etc. was accounted for. The emergy of sun radiation and wind were considerably lower than the emergy of rain or ET_{oa}. The decision, whether to choose the value of rain or ET_{oa}, usually depends on the prevailing hydrological and topographical properties of the system under study and on the decision of the author to account for accepted water or water used by the system (Campbell, 2003b). In our case we decided to choose the highest of both renewable emergy inflows separately in each individual year due to important differences in water conditions between the individual years.

In the system under study the geopotential emergy of water was assumed to be negligible due to the flatness of the area.

As local non-renewable (N) sources we usually consider loss of topsoil, exploitation of minerals and fuels etc. from within the system. In our case the only local non-renewable source were nitrogen losses from the system. The data about the itrogen cycle are given in the Chapter 3.3.4.4.

Notwithstanding the reports on frost-resistant properties of black alder the CIPER model implied that white frost affected annual increments. The contribution of white frost was accounted for through its effect on primary production. We assumed that one day of white frost caused a decrease of annual production corresponding to the one-week net primary production. This value was assumed based on the data that leaves usually need about three to four weeks to reach maximum photosynthesis (Eschenbach, 1995; Gochis and Cuenca, 1998; Granier et al., 2000b; Baldocchi and Wilson, 2001; Baldocchi et al., 2005; Črepinšek in Kajfež-Bogataj, 2005) and on the assumption that only the uppermost leaves were damaged, which accounted for about ¼ of leaves. UEV for white frost was assumed to equal the average UEV of NPP.

Purchased emergy inflows included emergy for growing seedlings, for stand preparation and for planting, for silvicultural measures including thinning and final cut, emergy for cutting wood into pieces and pulling the wood out of stand, and emergy for the road construction and maintenance. These data were calculated from the normatives for silvicultural work (Decree on Determination of Normative for Work in Forests, 1999) and from the data from the Forest Unit Lendava (Kolenko, personal communication, 2004; Forest Management Plans, 1992-2001).

Emergy for machinery, fuel, and human work was calculated according to the normatives for silvicultural work (Decree on determination of normative for work in forests, 1999). Services were calculated as the emergy equivalents of monetary costs. UEV of machinery and wood were obtained from Doherty (1995) whereas UEVs for human work and services were based on our own calculations for the year 2002 (Chapter 3.3.4.5). Invested mass and energy account for the work of nature whereas prices account for costs in machinery and fuel production. Weight, monetary costs, and amortization time of machinery are presented along with the calculation of emergy flows (Appendix E5).

The emergy of seedlings included the emergy of seeds and emergy for their cultivation until the age of two years including watering, cultivation and care (Nemesszeghy, 1968). Emergy of seeds was calculated through the area of stand needed to produce the necessary number of seeds, considering 20% germination faculty of seeds (McVean, 1953; Kotar, 2003), 80% survival rate in the first two years, the average mass of seed of 0,004 g/seed (Featherstone, 2003), the average production of 4000 catkins/tree (McVean, 1953) and the average of 60 seeds per catkin (Funk, 1990). Altogether we calculated that about 0,1 kg of seeds was needed, which is about 10,5% of annual production of a mature tree. Average biomass of a two-year-old seedling was calculated based on the Puhek's equation (Chapter 3.1.1.4) and the data on the density of alder wood (Wagenführ, 1996). The growing bed of 50 m^2 and 20 kg of seeds were needed to grow the sufficient number of seedlings needed for the stand of one hectare (Kotar, 2005) and the appropriate amount of solar and water emergy were needed to support seedling growth. We calculated that 15 minutes of tractor work were needed to prepare the area for planting and 10 hours of human work were needed for care and maintenance. According to the area of growing beds noted in the Forest Management Plans (1971-1980) one person can take care of one hectare of growing beds.

Emergy of inputs for road construction and maintenance included one-time building costs and yearly maintenance. Besides the investments of machinery and fuel needed to construct a road, we added also emergy of wood and gravel that were needed to consolidate the road (30 cm of gravel in 300 years and one layer of trunks with a diameter of 7 cm and with assumed life period of 200 years). The length of the road that belongs to one hectare of forests was estimated from the data on the average density of roads in the Forest Unit Polana (55,1 m/ha; Forest Management Plans, 2001-2011).

The costs for road construction were equally distributed among individual years of the lifetime of this road. All other costs were attributed to the year in which they took place. Emergy for seedling growth, for site preparation and for planting, for example, were all attributed to the first year of the stand growth.

For all renewable emergy inflows we calculated two different values. The first was their emergy contribution over the whole year and the second was their contribution over the growing season (Chapter 1.2.3.1). Emergies of purchased emergy flows were the same in both cases. This way we studied effects of attributes in two different time frames.

We assumed that biomass losses through diseases and through herbivores browsing were negligible.

3.3.4.2 Emergy of water

The amount of water in the stand was determined as the balance between inflows (precipitation and inflows of groundwater) and outflows (ET_{oa} and outflows of groundwater) into the system, as it was described in the Chapter 3.1.4.

To calculate the UEV of water stored in a stand we had to consider its cycle time (eq. 2 and 3). According to the calculated amount of water in the stand (4 m deep soil; see Chapter 3.3.2) and the average difference between annual precipitation and evapotranspiration the average retention time of five years was calculated for water in the stand if renewable flows over the whole year were taken into account. The adequate value was 8,8 years, if only renewable flows over the growing season were accounted for.

Average UEVs of stored water were calculated from:

$$UEV_{stored\ water} = (em_{rain/ETao}+em_{run\text{-}in\_gw})/(water_{stand}*\%_{cont}) \qquad (2)$$

Where: $em_{rain/ETao}$: emergy of higher among precipitation and ET_{oa}; $em_{run\text{-}in\_gw}$: emergy of groundwater inflows; $water_{stand}$: energy of potential chemical energy of water in the stand; $\%_{cont}$: annual contribution of rain that is not evapotranspired to the emergy of water storages ((precipitation–ET_{oa})/storage).

UEVs for water stored in the stand were calculated through the following equation:

$$UEV_{stored\ water} = (UEV_{rain}*\%_{runout}*(\%_{cont})^{-1}) + (UEV_{gw}*(1-(\%_{cont})^{-1})) \qquad (3)$$

Where: $UEV_{stored\ water}$: UEV of water storage in the stand; UEV_{rain}: UEV of rain (global average); UEV_{gw}: UEV of groundwater (see eq. 2); $\%_{runout}$: percent of rain that is not evapotranspired in individual year (it is assumed to run out); $\%_{cont}$: annual contribution of rain that is not evaporated, to the water storage ((precipitation–ET_{oa})/storage).

The calculation of emergy of water in the stand, like other emergy storages, followed the rules described in Tilley (1999), Odum (2003), and Tilley and Brown (2006):

- When stored energy was in steady-state, the accumulated emergy remained the same.
- When the energy storage was decreasing, the emergy lost was equal to the energy exported times its UEV.
- When the energy storage was increasing, the net accumulation of emergy was the sum of all inputs minus the exports of "used" emergy (e.g. removed wood or outflowing water).
- Exports carried away emergy with the UEV equal to that of the storage.
- Depreciations are processes necessary for the maintenance of the storage and they do not subtract emergy.

Changes in the Ledava River level could be attributed to the changes in water inflows and outflows as well as to hydroameliorations. In our model they affected both the expanse of annual increments and initial emergy storages in the stand, whereas water flows alone (precipitation, ET_a, run-in, and run-out) remained unchanged. The model enabled separate sensitivity analyses of the magnitude of water inflows (precipitation and run-in) and outflows of water from the system (ET_{oa}, runout).

3.3.4.3 Emergy of annual production, produced and removed wood

In our study we evaluated the amount of emergy needed for net primary production (NPP), for aboveground primary production, amounts of NPP invested into the aboveground wood, into the belowground tissue, into leaves, and into the remaining tissue (reproductive organs etc.). The calculation of physical flows (energy, mass or price) was described in the Chapter 3.3.4.1 and it is presented in the Appendix F5.

Volume increments of wood were calculated in the dendrochronological analysis (Chapter 3.1.1.4) and they, together with the data on the density of alder wood (510 kg/m^3; Wagenführ, 1996) and the data on the energy content of dry wood (19200 J/g; Tilley, 1999), enabled calculation of energy in wood.

To calculate annual net primary production (NPP), gross primary production (GPP), and parts of NPP invested into other parts of the tree, we used the data from Eschenbach (1995). We assumed that fixed part of GPP (41%) remained for NPP and that fixed part of NPP was invested into separate parts of a tree (wood: 22,08% of NPP, leaves: 20,48% NPP; roots: 37,06% of NPP). These data were obtained from a 53-year-old and 18 m high black alder tree in Germany (Eschenbach, 1995). Plant parts were regarded as coproducts. Annual data (wood increments, NPP, GPP) were summed to determine cumulative values.

Emergy inflows that were needed for wood production (Figure 18) were: higher among precipitation and ET_{oa}, white frost, nitrogen leaching, and purchased inflows needed in seed rising, planting, care, tree felling, and road construction. Produced wood included both standing trees and cumulative emergy of removed wood. It included the emergy for felling, but not the costs invested to get the wood out of the stand. To calculate emergy cost of removed wood we added emergy of purchased sources needed to cut wood into pieces and to pull it from the stand. The emergy for final felling was calculated separately to enable the comparison of both the UEV of wood in this year before felling and the UEV of removed wood.

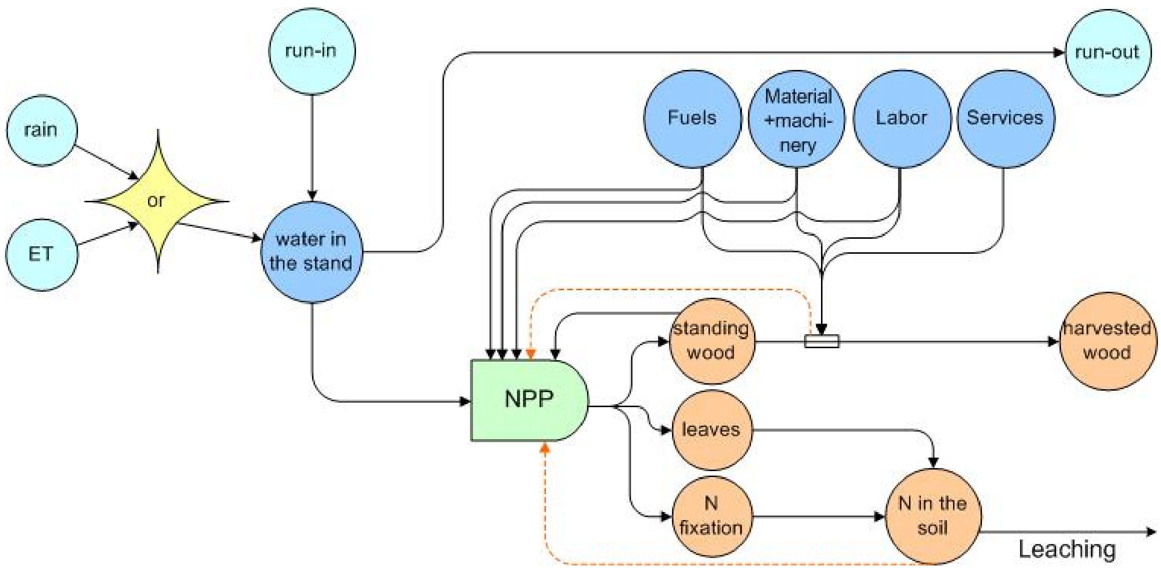


***Figure 18** Schematic representation of emergy flows that were important in UEVs calculation. Feedback flows that are marked with dashed orange lines were expected, but not proved in the discovered polynomial sub-model.*

Premature thinning measures are very important in the production process. This wood is sold and the early earnings help the owner to properly maintain the stand. At the same time they decrease competition between individual trees and they enable production of wood of a high quality. Thinning is therefore a self-reinforcing system. The emergy invested into the biomass that remained in the stand resulted in changed density of trees, decreased competition intensity, and in changed microclimatic conditions and source availability.

3.3.4.4 Emergy of nitrogen in the stand

The nitrogen fixation resulted in annual inputs of nitrogen to the stand. According to the literature (Chapter 1.2.3.9) it was assumed that annual fixation covered nitrogen needs for annual production of leaves and reproductive organs, whereas the rest of required nitrogen was obtained from the soil. Based on the data from the literature we assumed that 70% of total nitrogen required per year was fixed. Concentrations of nitrogen in black alder tissues were overviewed in the Chapter 1.2.3.9.

At the end of the season leaf-litter fell off trees and it degraded within a year. Consequently all nitrogen from the leaves contributed to the nitrogen in the soil within the following year. Part of mineralized nitrogen was used for biomass increments in the next growing season, part was stored in the soil (as long as nitrogen concentration in the soil did not surpass a soil storage capacity) and the rest was leached from the system. We assumed that the concentration of nitrogen in the soil below a mature stand was sustained. This assumption corresponded to the steady state conditions, whereas it would not be appropriate for developing and pioneer systems.

Due to the lack of measurements of nitrogen concentrations in the stand under study and measurements of the amount of nitrogen in the bedrock, the data on changes of nitrogen storages in the history were estimated based on the data from the literature (Kalan et al., 1988; Urbančič et al., 2000) and were reported with caution. Measurements that would be needed for accurate predictions were out of scope of this research.

UEVs of fixed nitrogen were calculated by multiplying UEV of annual net primary production by the factor 18,8. This factor corresponded to metabolic cost of 18,8 g of organic matter per gram of nitrogen fixation (see Chapter 1.2.3.9).

3.3.4.5 Emergy evaluation of Slovenia

The emergy synthesis of Slovenia was calculated for the year 2002. It was based on a template for emergy analyses of nations, which is available on the webpage of the Center for Environmental Policy, University of Florida (http://www.ees.ufl.edu/cep/tables.asp), although we applied UEVs values based upon the old planetary baseline (9,44E+024 sej/y). Emergy evaluation table of Slovenia and calculated performance indices are presented in the Appendix E.

The emergy evaluation of Slovenia was done for the last year, for which complete statistical data were available (2002). The data were achieved from SARS (Statistical Office of the Republic of Slovenia; http://www.stat.si/eng/index.asp; http://www.stat.si/doc/statinf/2004/si-158.pdf), Institute of Macroeconomic Analyses and Development (http://www.gov.si/zmar/aindex.php), ARSO (Environmental Agency of the Republic of Slovenia; http://www.arso.gov.si/podro~cja/), Chamber of Commerce and Industry for Slovenia (http://www.gzs.si/Nivo3.asp?IDpm=7738), and from BSP (Bank of Statistical Data; http://bsp1h.gov.si/D2300.kom/komstart.html). Some data were obtained directly from a Department for the Statistics of Production Activities at the Statistical Office of the Republic of Slovenia (amounts of excavated stones and mineral substances, amounts of produced cement).

The research considered constant UEV per person in all years under study. If we would be interested in the changes of the UEV of human work in time we should perform the emergy evaluation of Slovenia for all 69 years of the rotation period. As we were interested in the sustainability of the process as it is going on nowadays, we did not decide to use historical data. Besides this, the data needed for emergy evaluation of a nation are scarce and unreliable for the years before the independence of Slovenia (1991) and almost completely absent for years before the Second World War.

3.3.4.6 Performance indicators

In emergy evaluation tables we calculated different indices to draw inferences about changes in our system and to enable comparisons with similar researches. Indices were calculated in both emergy table and in computer model.

The most important performance indicators are (Ulgiati et al., 1995; Brown and McClanahan, 1996; Brown and Ulgiati, 1997; Brown et al., 2000; Brown, 2003):
- UEV (previously called solar transformity) itself evaluates the quality of the energy flows. It can be regarded a measure of the hierarchical position of an energy flow or storage, when we compare different products (Odum, 2003). It is also a measure of the efficiency of a process (Raguei et al., 2005; Ulgiati et al., 2005) and quality of the product (Bastianoni et al., 2001) when we compare processes generating the same products. It is very effective evaluation parameter and it is sensitive to changes in any emergy flow that is fed to the system.
- The Emergy Yield Ratio (EYR = U_Y/(M+S)) is the ratio of the total emergy used to generate the input (Y) divided by the emergy of these inputs that are fed back from outside to the systems under study. It gives a measure of the ability of the process to exploit local resources and to make them available (Odum, 1996; Ulgiati et al., 2005). It is a measure of the contribution of the process to the economy beyond its own operation. Ratios around one indicate that a process uses similar amount of emergy from the economy as it contributes (Odum, 1996). Care must be taken to avoid misinterpretations of this index. It measures the potential, not actual contribution and consequently it does not tell anything about the efficiency of the process (Raguei et al., 2005; Ulgiati et al., 2005).
- The Emergy Loading Ratio (ELR = (N+M+S)/R)) is the ratio of purchased (M+S) and nonrenewable local emergy (N) to free environmental emergy (R). It is an indicator of the pressure on the local ecosystem. It can be considered a measure of ecosystem stress caused by the production activity (Brown and Ulgiati, 1997), but not a measure of the actual pollution (Ulgiati et al., 2005). It measures the intensity (“distance”) of the process relative to the productive ability of the natural environment (Tilley and Swank, 2003; Ulgiati et al., 2005).
- Empower density is the emergy per unit of time and per unit of area. It is a relative measure of the intensity of the activity (Brown, 2003).

Several other indicators exist, which are mostly derived from the first three above (Ulgiati et al., 2005). Some of them are:
- The Renewable Emergy Fraction (%R or REF) is the percent of the total energy driving a process that is derived from renewable sources (%R = R/(R+N+M+S) = R/Y = 1/(1+ELR)). In the long run only processes with high %R are sustainable.
- The Nonrenewable to Renewable Ratio ((N+M+S)/R). High ratios indicate processes that match high amount of nonrenewables to relatively small flows of emergy.

- The Emergy Sustainability Index (SI or ESI = EYR/ELR) is defined as the ratio of the EYR to the ELR. It globally measures if a process provides a suitable contribution to the user, at low environmental pressure (Ulgiati and Brown, 1998). It is a function of yield, renewability and load on the environment. The higher this index the more an economy relies on locally renewable energy sources and minimizes imports and environmental load (Brown and Ulgiati, 1999). However, some authors try to avoid this index, because a ratio of indices causes a loss of information.
- Emergy Investment Ratio (EIR = (M+S)/(R+N) = 1/(EYR-1)) is the ratio of the emergy that is fed back from the economy to the emergy inputs from the free environment. This ratio indicates if the process is economical as utilizer of the economy's investments in comparison to alternatives (Odum, 2000). It measures the intensity of economic development and the loading of the environment. In highly developed countries EIR tends to be 7 or higher (Odum, 1996).

Resource indices, emergy summations and graphical analyses were used to synthesize evaluations and to discuss alternatives regarding forest use and management. Both UEVs of annual increments and UEVs of standing biomass were studied.

We searched for correlations among UEVs and radial increments as well as correlations between emergy indices and annual increments. These correlations were studied to find out to which extent energy indices can tell us what is going on with the ecosystem and its function.

3.4 Computer simulation model

In the present study the computer simulation model built was built on two bases: the sub-model generated with equation discovery tools and the emergy accounting procedure. Both of them were dependent on several attributes describing environmental conditions and management in individual years. The modeling showed its advantages in combined simultaneous simulation of annual increments and adequate emergy indices under different environmental conditions.

An important advantage of ecological models is the sensitivity analysis. It enables tracing of changes in flows or storages under interest when individual attributes or their combinations are changed. It also enables identification of the most important attributes.

3.4.1 STELLA modeling software

To construct our model we needed an appropriate computer-modeling tool. This tool had to be:
- Appropriate for systems analyses: it should allow several feedback loops, it should include sub-models, etc.
- Surveyable, clear.
- Flexible: it should allow simple addition, removal or modification of the data, inputs and variables.
- Accessible, tested and valued.
- It should allow simultaneous simulation of several attributes and additional comparison of results, statistical analyses and sensitivity analyses.

STELLA has proved to be an appropriate tool in ecological modeling and in sustainability assessment (Costanza and Ruth, 1998; Jørgensen, 1999; Costanza et al., 2002). In STELLA the essential features of the system are defined in terms of stocks, flows, auxiliary variables (constants, mathematical or graphical functions or data sets), and information flows (Figure 19). Once the structure of the model is laid out on the screen, initial conditions, parameter values, and functional relationships can be specified. Sub-models enable overview on how each part of the model performs and in this way they enable elimination of eventual mistakes.

Specification of initial conditions, parameter values and functional relationships is enabled by clicking on the icons of state variables and writing the data needed into dialogue boxes. As the input data we can use single numerical values or we can define graphical or mathematical functions (Figure 19B, C). A set of difference equations is generated through this process, which can be viewed and manipulated directly or exported to other modeling environments. The sensitivity of the model to changes in the attribute values can be assessed either by varying attributes with sliders or by using built-in sensitivity analyses, specified in a separate dialogue box. More information can be found in the articles written by Costanza et al. (1998) and Costanza and Voinov (2001), in the STELLA tutorial, etc.

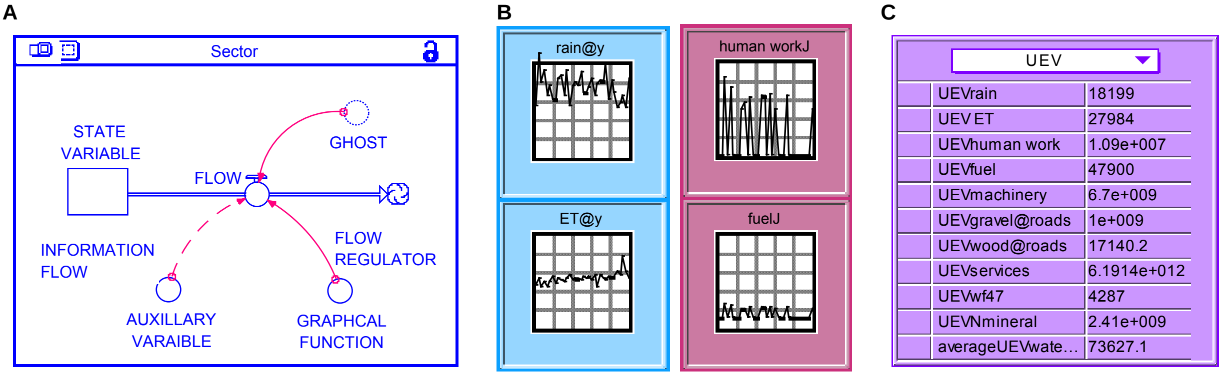


Figure 19 *A fragment of the STELLA model showing the most common building blocks (A). Examples of graphical input devices (modified from Costanza et al., 1998) (B) and list input devices in the STELLA model (C).*

As a result of the STELLA simulation we can get a graphical representation, a table of end-values, or a table of intermediate (at chosen time steps) and end-values. It is possible to change the simulation periods, to add switches, to use different integration methods, to display “warning” messages, to use animations, to use different designing possibilities, etc.

The program runs on three levels:
- Interface level: This level shows us the general structure of the model. Stocks representing submodels and connections among them are shown. At the same time this level shows different switches and values of selected attributes (Figure 19B, C). Here we can easily and reversibly change initial values of individual attributes (stocks, flows, actions, switches, etc.).
- Map/model level: This level shows the particular composition of the model, together with all connections and relations (Figure 19A, Appendix G).
- Equation level: This level shows us mathematical relationships between individual model components. We can also use this level just as an overview, as it is possible to manage the model only through partial equations of each individual flow at the map/model level.

Model’s sensitivity to attribute changes can be assessed either by manual modifications of attributes or through the built-in sensitivity analyses (Costanza et al., 1998; Costanza and Voinov, 2001).

STELLA software includes a procedural programming language that is useful to view and to analyze difference equations that are created as a result of manipulating icons. Consequently the building-block structure of STELLA enables the user to avoid complex mathematical functions, as the program itself combines equations describing relations among separate attributes into complex differential equations.

Through the modeling approach it is possible to use the real data instead of long-term averages for each individual input. In this way we can overview oscillations of each resulting value in time (amounts of products, energy of each particular quality consumed, UEVs and other emergy indices). At the same time this can help us to better understand the role of particular functions, constants, and storages. Computer models can help us to deeply understand processes. The observations and interpretations of simulation results can help us to get new insights into the properties of the process.

3.4.2 Model construction

The submodel generated by the equation discovery tool (eq. 4) was used to construct a simulation model. Our goal was to construct a dynamic model of radial increments of black alder trees under study and emergy evaluation model.

Due to differences in the attributes driving the model on radial increments and emergy synthesis it was not possible to construct a single model for both annual increments and their emergy synthesis. Both processes were run in parallel and their results were linked in the last modeling steps.

The model was calibrated with the data measured in the stand and with the data from the literature. The submodel on annual increments was calibrated by the results of the equation discovery tool to achieve the highest possible validity. The most important responses of radial increments were included within this submodel and they cannot be added to other parts of the model. The part of the model dealing with emergy synthesis of the system under study strictly followed the rules on emergy synthesis as they were described in the Chapter 3.3.4.

The schematic overview on the model structure is given in the Figure 20, whereas the structure of the whole model is presented in the Appendix G. The presentation includes the schematic overview of the map/model level and a copy of the equation level of the STELLA model.

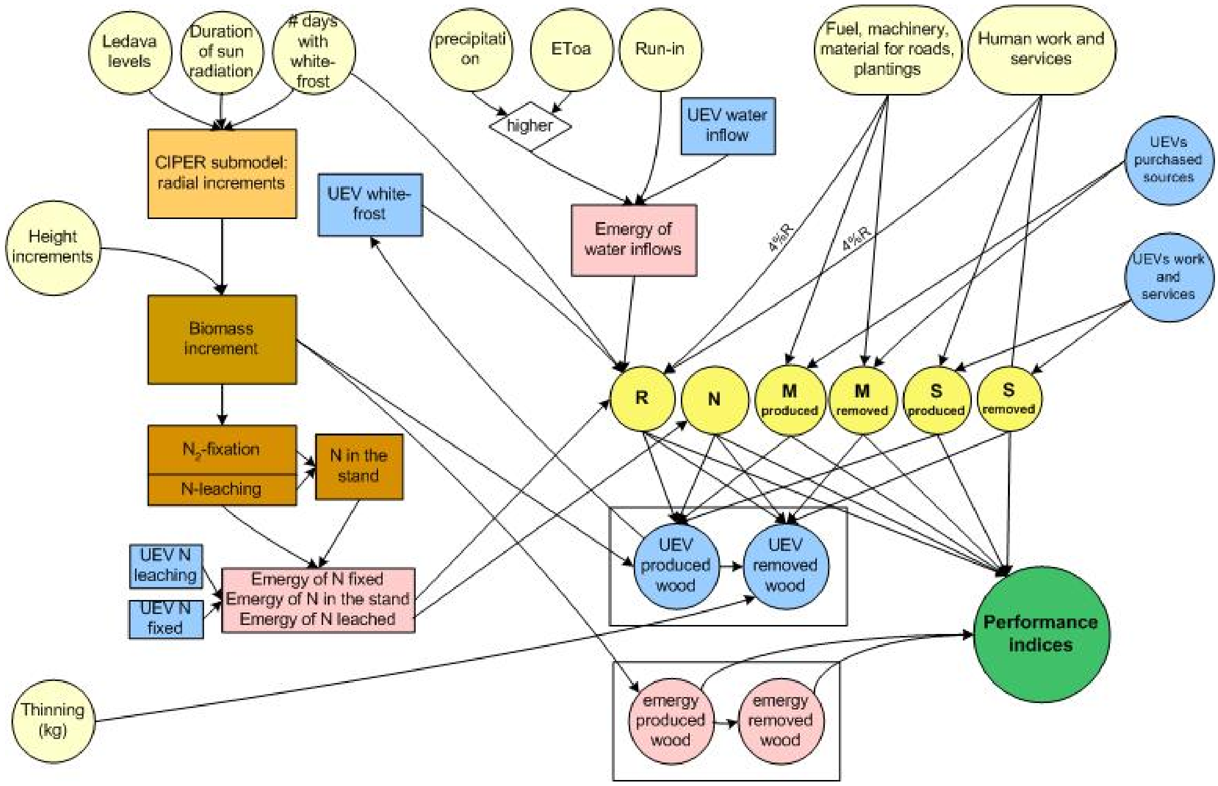


***Figure 20** Schematic overview of the constructed model presenting the major sectors and connections among them.*

At each step in the constructing process the model was verified whether it calculates expected values and if it behaves in the expected manner. This ensured that there were no computational, structural or conceptual errors. At the same time we determined limits of possible attribute values to avoid incorrect model behavior. The first validation test was 10-times cross validation of the submodel generated with CIPER. Besides, the model was tested for its behavior under different conditions to validate the model assumptions. The possibilities to validate finished emergy-based model were limited, as no reference exists in the nature for comparison of emergy indices.

Several sensitivity analyses were run to validate the model. The sensitivity analysis is a systematic exploration of model responses (Odum, 1996). In common sensitivity analyses the model compared the results of the model as one or more attributes were changing within the observed data range. In this way it was possible to compare results under changing constant values of attributes. Besides, we used a somewhat different sensitivity analysis, which enabled tracing of consequences of changed annual values in graphical functions: the model was run at original values of attributes, as well as at 25% increased and 25% decreased values of individual attributes. Different attribute combinations were tested as well (Figure 32).

The models helped us to compare modeled and measured values in individual years (e.g. Appendix C, column A) and under different scenarios. The implication of the modeling tool makes this process faster, easier and considerably more clear. The model enables overview on which attributes were changed and immediate return to default conditions.

All emergy indices were calculated in two different ways: with or without purchased inputs. A switch in the model enabled very fast change from one option to the other. Graphs and tables that were obtained from the computer simulations enabled overview of the data and their comparisons.

Our model cannot be considered as the completely dynamic model as the submodel generated by the CIPER did not account for the time dimension. Besides, it was not possible to define all attributes in terms of differential or difference equations due to the lack of the data on some linkages among individual environmental factors and between the corresponding responses of the stand. To distinguish it from what is called dynamic models we used the term temporary-dynamic model. It showed changes in the environment in time, but time-dependent trends were not defined in the model structure.

4 RESULTS

This chapter unfolds the results of the data mining and the modeling. At the beginning the results of feature selection procedure are presented, followed by results of both machine learning approaches: model and regression trees, and equation discovery. The chapter continues with results of emergy accounting of the forest stand in 35 years under study. At the end the results of machine learning approach and the emergy synthesis are joined to enable construction of an ecological model on emergy accounting of the black alder stand.

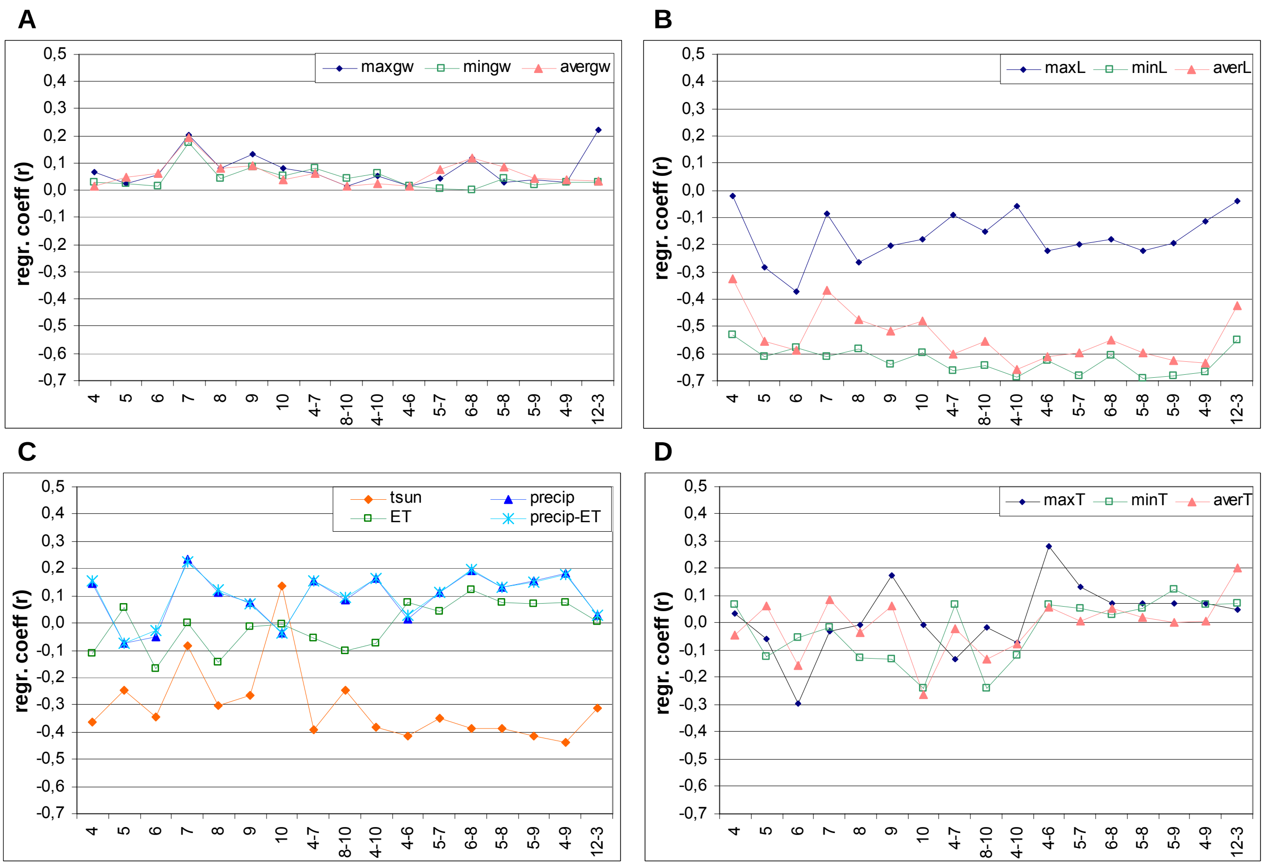
The results of measurements in the forest stand were shown in the Chapter 3.

4.1 Data mining

4.1.1 Feature selection

Feature selection was performed through the statistical analyses. In the search for hydrological, meteorological and management attributes, which most likely affected the average annual radial increments of the eight trees under study (Chapter 3.1.1.2), we applied Pearson's (or linear) correlation and linear regression. Altogether 333 attributes were included in the analyses, including monthly and average periodical values of management, meteorological, and hydrological attributes (Chapter 3.1.2, 3.1.3, 3.1.4). In the following average monthly values were represented by the serial number of the month in a year (see Chapter 3.1.3).

The majority of determined regression correlation coefficients and their changes over the year are presented in the Figure 21. Each point was determined independently and lines between them were added only for better overview. The attributes for which only annual values were available are presented in the Table 8.



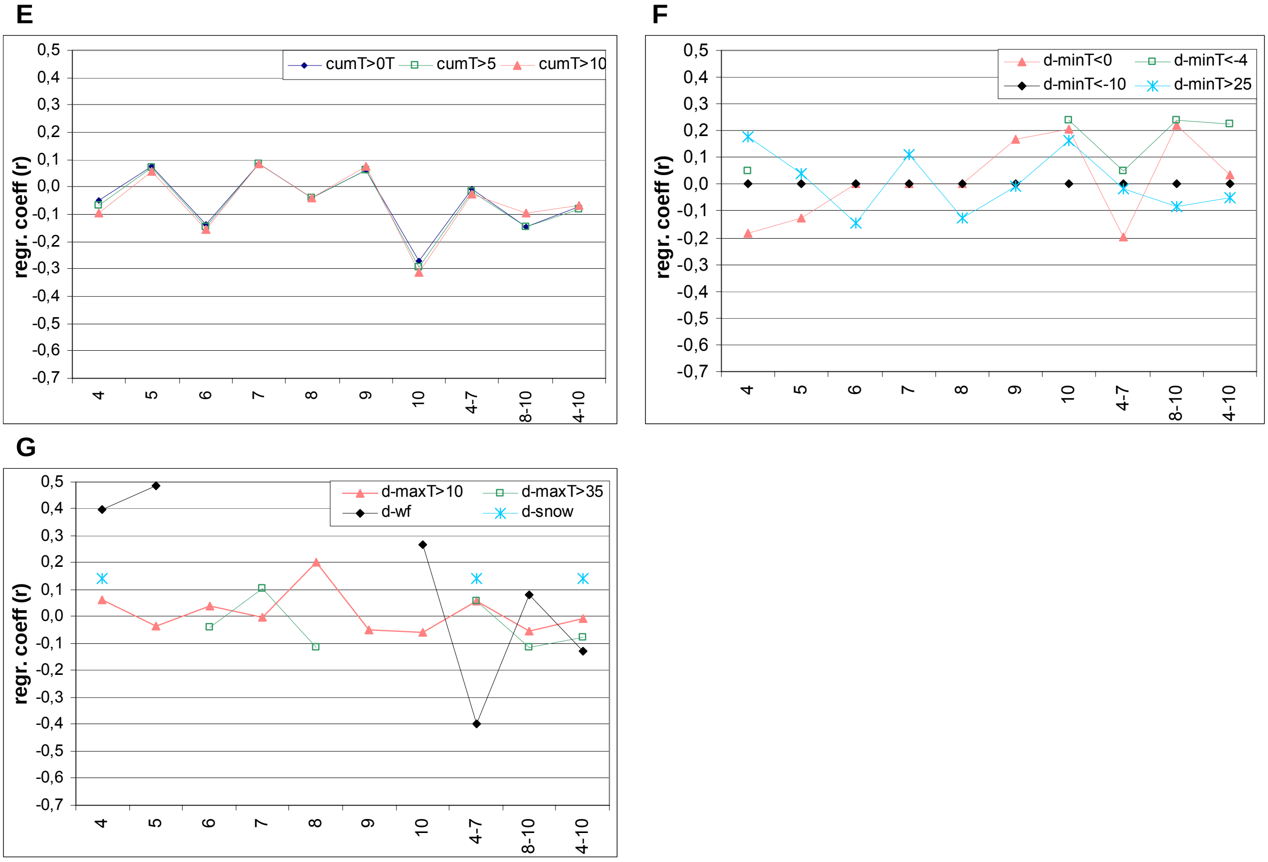


Figure 21 *Response functions of radial increments on **A**) the groundwater levels in a given period; **B**) the Ledava River levels; **C**) the duration of sun radiation (tsun; hours); precipitation (prec; mm); reference evapotranspiration (ET_o), and the difference between precipitation and ET_o; **D**) the maximum, average, and minimum temperature in a given period; **E**) the cumulative temperatures above 0°C, 5°C, and 10°C (cumT>0, cumT>5 and cumT>10); **F**) the number of days with minimum temperature below 0°C, below -4°C, below -10°C, and above 25°C (d-minT<0, d-minT<-4, d-minT<-10, d-minT>25); **G**) the number of days with maximum temperature above 10°C (d-minT>10) and above 35°C (d-minT>35), the number of days with white frost between April and July (dwf4-7) and the number of days with snow in the previous winter (d-snow). In some months no variance in the data was observed.*

Table 8 *Regression correlation coefficients of radial increments and attributes that were available only for annual periods.*

attribute	**r** (p = 0,05)
age	*-0,619*
thinning	*-0,398*
thinn_y-1	*-0,149*
thinn_y-2	*0,076*
thinn_y-3	*0,026*
Branan	*-0,064*
Huglin	*-0,069*

(age: the age of the stand in individual year; thinning: the thinning measures performed in the individual years; thinn_y-1, thinn_y-2, thinn_y-3: the thinning measures performed in the previous year, two years ago, and three years ago; Branan: Branan's value, heliothermic sum; Huglin: Huglin's heliothermic index).

Linear regression showed that the minimum Ledava River level had the highest degree of correlation with the radial increments (Figure 21). The other attributes with the absolute value of regression correlation coefficients equal or higher of 0,4 were the maximum and the average Ledava River levels, sun radiation and the number of days with white frost in the spring (dwf4-7). Black alder growth seemed to be relatively indifferent to the observed temperature fluctuations. The correlation dependence with radial increments was low also for precipitation (prec), ET_o and for the drought stress index (prec-ET_o).

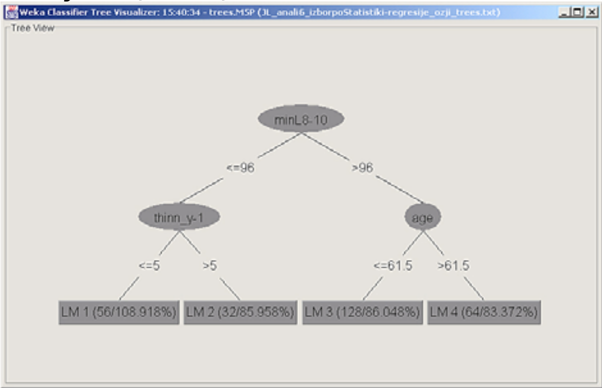
4.1.2 Model and regression trees

Several different models were generated with the M5' algorithm in WEKA. The comparison of model results is given in the Appendix B, Figures B1, B2 and B3. These figures compare correlation coefficients, regression correlation coefficients, and Root Relative Square Error (RRSE) values of models (model and regression trees) generated with different sets of attributes (analyses 1-8; Table 5) and at different degrees of pruning. Some parts of pictures are enlarged to better distinguish individual values at critical points.

Models with the highest correlation and regression correlation coefficients, and with the lowest RRSE were precisely studied. Three analyses were selected for the future work: analyses 2, 6 and 7. Their model and regression trees generated under a restriction of minimum 50 cases in each leaf are presented in the Figure 22, Figure 23 and Figure 25.

Delimiting values (values in the nodules of the model and regression trees) of the analyses 2, 6 and 7 together with observed values of individual attributes are presented in the Appendix B, Figure B4.

analysis 6, M=50; model tree



LM num: 1
*r- tree = -0,0015 * age*
*+ 0,0204 * thinn*
*- 0,0004 * thinn_y-1*
*- 0,001 * minL7*
*- 0,0019 * minL8-10*
*- 0,0001 * tsun4-7*
*- 0,0179 * dwf_4-7*
+ 2,9089

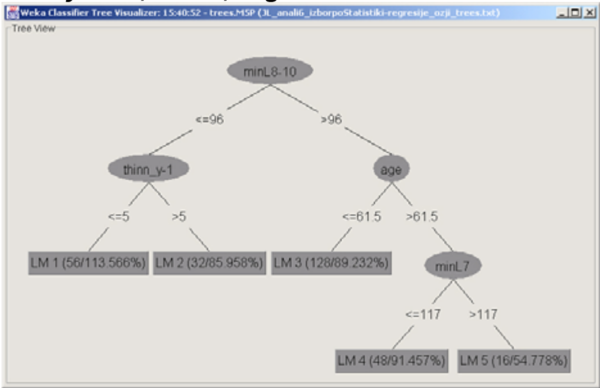
LM num: 2
*r- tree = -0,0015 * age*
*+ 0,0085 * thinn*
*- 0,0005 * thinn_y-1*
*- 0,001 * minL7*
*- 0,0019 * minL8-10*
*- 0,0001 * tsun4-7*
*- 0,0179 * dwf_4-7*
+ 2,491

LM num: 3
*r- tree = -0,0023 * age*
*- 0,0001 * thinn_y-1*
*- 0,0064 * minL7*
*- 0,0009 * minL8-10*
*- 0,0001 * tsun4-7*
*- 0,1164 * dwf_4-7*
+ 2,8123

LM num: 4
*r- tree = -0,0035 * age*
*- 0,0001 * thinn_y-1*
*- 0,0213 * minL7*
*- 0,0009 * minL8-10*
*- 0,0001 * tsun4-7*
*- 0,0211 * dwf_4-7*
+ 4,1463

Correlation coefficient	*0,6339*
Mean absolute error	*0,4347*
Root mean squared error	*0,5227*
Relative absolute error	*80,2588 %*
Root relative squared error	*77,2678 %*

analysis 6, M=50; regression tree



LM num: 1
r- tree = + 2,4536

LM num: 2
r- tree = + 1,9659

LM num: 3
r- tree = + 1,7217

LM num: 4
r- tree = + 1,5071

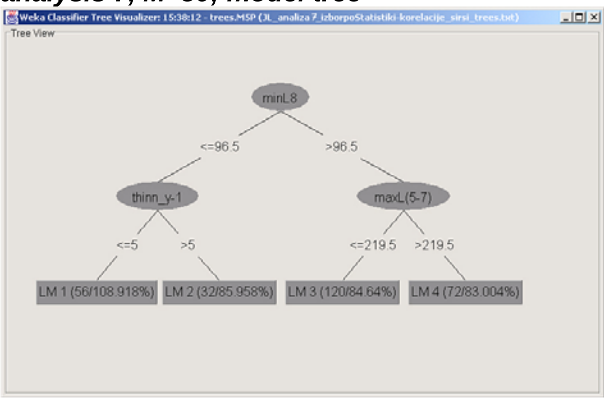
LM num: 5
r- tree = + 1,2336

Correlation coefficient	*0,6187*
Mean absolute error	*0,4449*
Root mean squared error	*0,5354*
Relative absolute error	*82,1441 %*
Root relative squared error	*79,1398 %*

Figure 22 *Model (left) and regression trees (right) of the first selected WEKA model: analysis 6.*
Evaluation values were based on 10x cross validation. M5' model trees were built using smoothed linear models and they were pruned to a minimum of 50 examples per leaf (M).

(age: the age of the stand in the individual year; thinn: the thinning measures performed before the current growing season; thinn_y-1: the thinning measures performed before the previous growing season; minL7: the minimum level of the Ledava River in July; minL8-10: the minimum level of the Ledava River between August and October; tsun4-7: the duration of sun radiation between April and July; dwf_4-7: the number of days with white frost between April and July).

analysis 7, M=50; model tree



LM num: 1
*r- tree = 0,0204 * thinn*
*- 0,0004 * thinn_y-1*
*- 0,0002 * maxL5-7*
*- 0,0011 * minL8*
*- 0,0036 * minL5-8*
*+ 0,0009 * averL4-7*
*- 0,0002 * tsun4-9*
*+ 0,0002 * precip7*
+ 3,0823

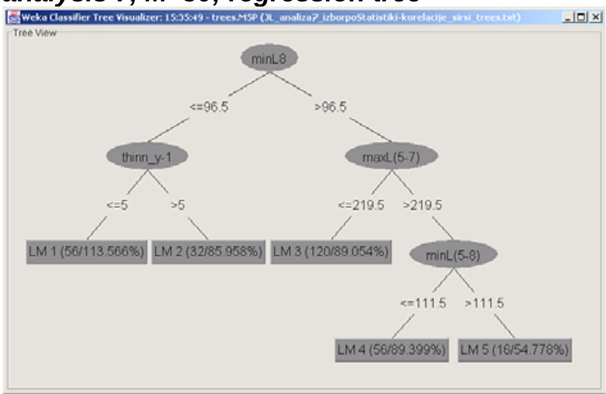
LM num: 2
*r- tree = 0,0085 * thinn*
*- 0,0005 * thinn_y-1*
*- 0,0002 * maxL5-7*
*- 0,0011 * minL8*
*- 0,0036 * minL5-8*
*+ 0,0009 * averL4-7*
*- 0,0002 * tsun4-9*
*+ 0,0002 * precip7*
+ 2,6645

LM num: 3
*r- tree = 0 * thinn_y-1*
*- 0,0005 * maxL5-7*
*- 0,0006 * minL8*
*- 0,0052 * minL5-8*
*+ 0,0026 * averL4-7*
*- 0,0011 * tsun4-9*
*- 0,0022 * precip7*
+ 3,8485

LM num: 4
*r- tree = 0 * thinn_y-1*
*- 0,0006 * maxL5-7*
*- 0,0006 * minL8*
*- 0,0411 * minL5-8*
*+ 0,0199 * averL4-7*
*- 0,0003 * tsun4-9*
*+ 0,0001 * precip7*
+ 3,7336

Correlation coefficient	*0,6293*
Mean absolute error	*0,4366*
Root mean squared error	*0,5254*
Relative absolute error	*80,6194 %*
Root relative squared error	*77,6579 %*

analysis 7, M=50; regression tree



LM num: 1
r- tree = + 2,4536

LM num: 2
r- tree = + 1,9659

LM num: 3
r- tree = + 1,736

LM num: 4
r- tree = + 1,5068

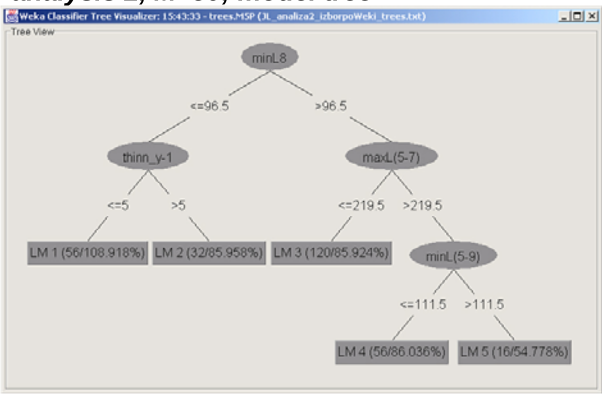
LM num: 5
r- tree = + 1,2303

Correlation coefficient	*0,6123*
Mean absolute error	*0,4473*
Root mean squared error	*0,5383*
Relative absolute error	*82,5802 %*
Root relative squared error	*79,5684 %*

Figure 23 *Model (left) and regression trees (right) of the second selected WEKA model: analysis 7.*
Evaluation values were based on 10x cross validation. M5' model trees were built using smoothed linear models and they were pruned to a minimum of 50 examples per leaf (M).

(maxL5-7: the maximum level of the Ledava River between May and July; minL8: the minimum level of the Ledava River in August; minL5-8: the minimum level of the Ledava River between May and August; averL4-7: the average level of the Ledava River between April and July; tsun4-9: the duration of sun radiation between April and September; precip7: the average amount of precipitation in July; the other abbreviations are explained in the Figure 22).

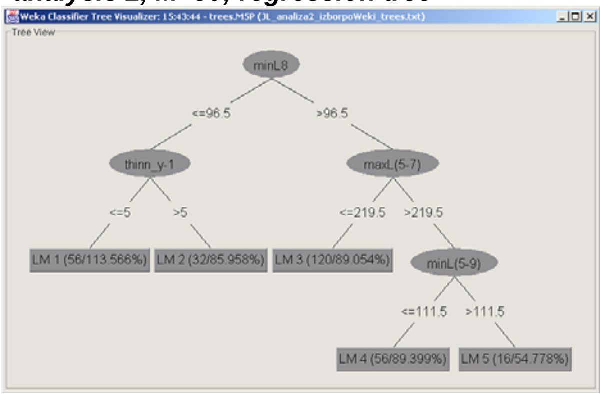
analysis 2, M=50; model tree



LM num: 1
r-tree =
*0,0204 * thinn*
*- 0,0004 * thinn_y-1*
*- 0,0009 * minL8*
*- 0,0032 * minL5-9*
*- 0,0002 * tsun4-9*
*- 0,0053 * minT4-10*
+ 3,1095
LM num: 2
r- tree =
*0,0085 * thinn*
*- 0,0005 * thinn_y-1*
*- 0,0009 * minL8*
*- 0,0032 * minL5-9*
*- 0,0002 * tsun4-9*
*- 0,0053 * minT4-10*
+ 2,6916
LM num: 3
r- tree =
*0 * thinn_y-1*
*- 0,0002 * maxL5-7*
*- 0,0004 * minL8*
*- 0,0033 * minL5-9*
*- 0,0011 * tsun4-9*
*- 0,0026 * minT4-10*
+ 3,5868
LM num: 4
r- tree =
*0 * thinn_y-1*
*+ 0,0027 * maxL8*
*- 0,0003 * maxL5-7*
*- 0,0004 * minL8*
*- 0,0093 * minL5-9*
*- 0,0003 * tsun4-9*
*- 0,0026 * minT4-10*
+ 2,4714
LM num: 5
r- tree =
*0 * thinn_y-1*
*+ 0,0013 * maxL8*
*- 0,0003 * maxL5-7*
*- 0,0004 * minL8*
*- 0,0159 * minL5-9*
*- 0,0003 * tsun4-9*
*- 0,0026 * minT4-10*
+ 3,1355

Correlation coefficient	*0,6326*
Mean absolute error	*0,4392*
Root mean squared error	*0,5238*
Relative absolute error	*81,0996 %*
Root relative squared error	*77,4215 %*

analysis 2, M=50; regression tree



LM num: 1
r- tree = + 2,4536

LM num: 2
r- tree = + 1,9659

LM num: 3
r- tree = + 1,736

LM num: 4
r- trees = + 1,5068

LM num: 5
r- tree = + 1,2303

Correlation coefficient	*0,607*
Mean absolute error	*0,4498*
Root mean squared error	*0,5406*
Relative absolute error	*83,0568 %*
Root relative squared error	*79,9108 %*

Figure 24 *Model (left) and regression trees (right) of the third selected WEKA model: analysis 2. Evaluation values were based on 10x cross validation. M5' model trees were built using smoothed linear models and they were pruned to a minimum of 50 examples per leaf (M).*

(minL5-9: the minimum level of the Ledava River between May and August, minT4-10: the minimum temperature between April and October; the other abbreviations are explained in the Figure 22 and in the Figure 23).

Among these three models the model of the analysis 6 (M=50) was chosen as the most reliable and the most prospective. This model was ranked the best in all selection criteria: the magnitude of correlation (Appendix B, Figure B1), the regression correlation coefficients (Appendix B, Figure B2), and the RRSE (Appendix B, Figure B3). Moreover, we considered the complexity of the model (the number of leaves in the tree) and the reasonableness of the generated sub-models (coincidence of statistical results and the sign and the magnitude of impacts of individual attributes on annual increments).

The attributes that were included in the selected model, were:
- age;
- the thinning measures performed before the current growing season (thinn) and before the previous growing season (thinn_y-1);
- the minimum level of the Ledava River in July (minL7) and between August and October (minL4-10);
- the duration of the sun radiation between April and July (tsun4-7);
- number of days with white frost in the spring (dwf4-7).

The model divided the annual increments into four different groups (named leaves in regression and model trees). Values of the average modeled and measured increments in each leaf are shown in the Figure 25. The model predicted the highest radial increments in years with low minimum levels of the Ledava River at the end of the growing season. Increments were the lowest in years with relatively high minimum Ledava River levels in the second part of the growing season, especially in the last years before felling.

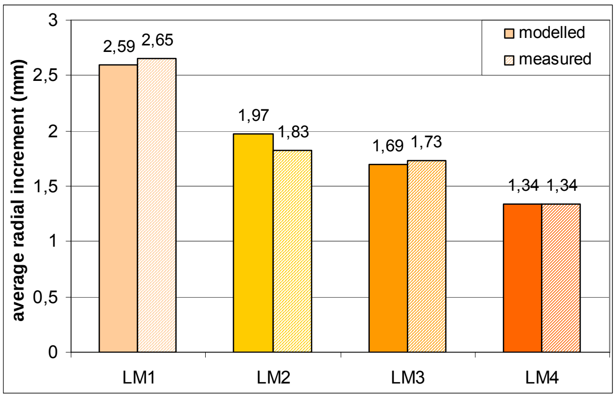


Figure 25 *Average predicted (filled columns) and measured (striped columns) values of radial increments in each leaf of the regression tree of the analysis 6, M=50.*

Due to the different range of values of individual attributes in this model we cannot say anything about the importance of individual attributes for changes in annual increments. To get an insight into the performance of the modeled radial increments under changing values of individual attributes and combinations of different values of attributes we constructed an ecological model in the STELLA software and we run sensitivity analyses during the modeling step. The Figure 26 presents the model constructed from the data mining results of the analysis 6. The Figure 27 compares measured average radial increments of the eight trees and increments predicted by the selected model tree (analysis 6, M=50).

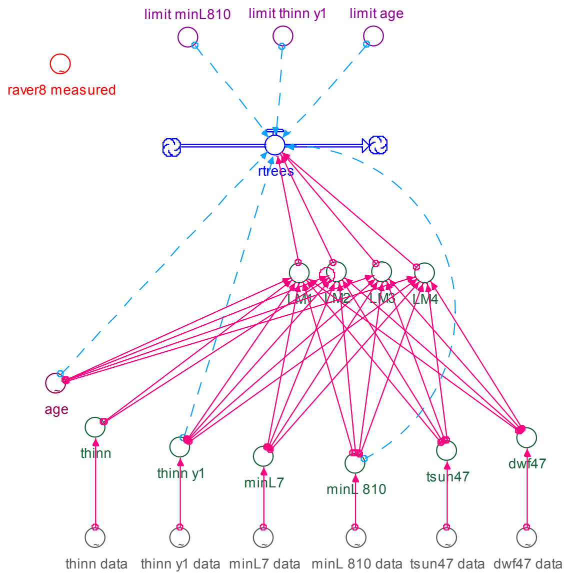


Figure 26 *The schematic representation of the model tree of the analysis 6, as it was constructed in the STELLA software.*

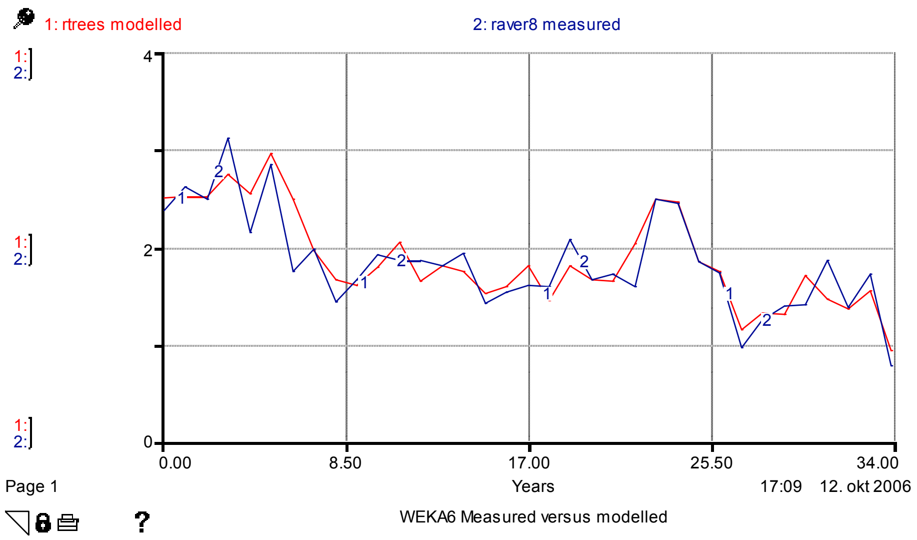


Figure 27 *The comparison of average radial increments that were measured on stem disks (level 1) and values that were calculated by the model tree of the analysis 6.*

Several different sensitivity analyses were performed. Some of them were run to show changes in predicted radial increments:

- during the transition from dry and sunny toward wet and cloudy conditions (Figure 28);
- at different thinning intensities before the current growing season (thinn; Appendix B, Figure B5A); effects at the age of 35 years and at the age of 69 years are presented;
- at different thinning intensities in the previous year (thinn_y-1; Appendix B, Figure B5B);
- at different minimum levels of the Ledava River in July (minL7; Appendix B, Figure B5C);
- at different minimum levels of the Ledava River between August and October (minL8-10; Appendix B, Figure B5D);
- at different duration of sun radiation in the first part of the growing season (tsun4-7; Appendix B, Figure B5E);
- at different number of days with white frost in the spring (dwf4-7; Appendix B, Figure B5F).

The comparison between the average measured radial increment (x) and the increment predicted by the model (y) resulted in a regression equation of y = 0,87x+0,2341. The corresponding regression correlation coefficient was 0,884.

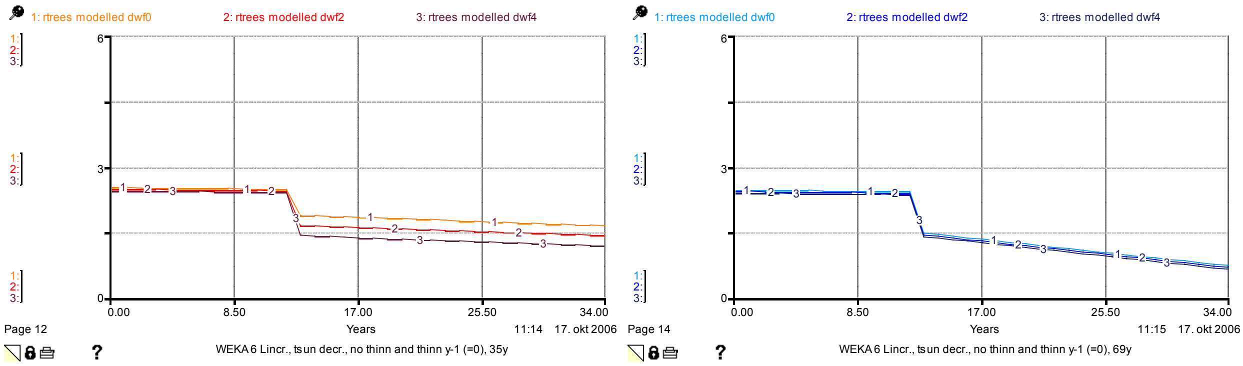


Figure 28 *Effects of the shift from dry and sunny toward rainy and cloudy years (Lincr, tsun47decr) at three different levels of white frost in the spring (dwf4-7; 1: none; 2: 2 days; 3: 4 days). Intensities of thinning (thinn and thinn y-1) were set to zero. Changes at the age of 35 years (left) and at the age of 69 years (right) are presented.*

In the Figure 28 we can see that the response to the linear increase in the groundwater level and the corresponding linear decrease in the duration of sun radiation was highly non-linear. This occured because of the nonlinear transition between equations in individual branches of the model tree (LM1, LM2, LM3 and LM4). The response was similar at the age of 35 years and at the age of 69 years, although a decrease in sensitivity to white frost was observed with ageing.

The sensitivity analyses revealed that the most intense changes were induced by thinning measures and by changes in the Ledava River levels in the second part of the growing season. In many cases changes in predicted increments were sudden and hardly explainable.

The Table B1 in the Appendix B compares the attributes selected by the model tree generating algorithm (analysis 6) and corresponding regression correlation coefficients as they were calculated through linear regression during the statistical analyses of average measured radial increments and values of corresponding attributes.

4.1.3 Equation discovery

The next experiment was intended to explore the applicability of equation discovery algorithm CIPER in describing the dependence of annual increments on environmental and management conditions. As it was explained in the Chapter 3.2.3.1, 52 different combinations of 6-10 attributes were tested. Each combination was run under different complexity constrictions, which finally resulted in 124 experiments. Among these 124 experiments we made further selection based on the observed Root Relative Squared Error (RRSE), as an indicator of the error of predictions, on the complexity of the model, and acceptableness of the mathematical relations between components. 15 models remained after this selection and they were subjected to testing under changing environmental conditions and to the sensitivity analyses in the STELLA modeling software. Equation complexity (Table 9), especially equation degree, was considered as well. Three of them were immediately rejected due to unacceptable responses. The characteristics of the remaining 12 experiments are noted in the Table 9. The comparison of the average measured annual increments and the radial increments predicted by each of 12 models, are presented in the Appendix C1. These figures present also predicted radial increments of the trees under the increasing Ledava River levels in combination with the decreasing duration of sun radiation. If the appearance of white frost was determined as a component of the model, then each simulation was run under three different levels of white frost. Moreover, each sensitivity analysis was performed at the age of 35 years and at the age of 69 years, if the polynomial model accounted for the time dimension.

***Table 9** A comparison of root relative squared error (RRSE) and indicators of the equation complexity for 12 selected polynomial models.*

	Model	RRSE	# of attributes in the equation	Equation size*	Equation degree*	Equation length*
1	*Jnj3_2m*	*0,7282*	*6*	*12*	*2*	*19*
2	*Jnj3_3s*	*0,7599*	*6*	*8*	*3*	*13*
3	*Jnj3_1s*	*0,7614*	*6*	*8*	*3*	*12*
4	*Jnj3_4m*	*0,7645*	*3*	*7*	*3*	*13*
5	*Jnj2_2*	*0,7685*	*5*	*11*	*3*	*19*
6	*Jly_4xl*	*0,7686*	*6*	*11*	*3*	*20*
7	*Jly_3al*	*0,7720*	*6*	*12*	*2*	*10*
8	*Avg_3hxl*	*0,7746*	*6*	*5*	*7*	*14*
9	*Jnj2_3m*	*0,7748*	*6*	*11*	*3*	*19*
10	*Jnj1_4*	*0,7839*	*3*	*7*	*6*	*22*
11	*Avg_3al*	*0,7887*	*4*	*4*	*3*	*7*
12	*Jnj2_2s*	*0,8060*	*5*	*6*	*3*	*10*

**The size of the equation is the number of polynomial terms in the equation; equation degree is the largest degree of any one term; equation length is the sum of exponents of the variables.*

The model Jnj3_2m has proved to have the highest coincidence with the measured data (Table 9) and the most prospective behavior (Table 9 and comparison of models in the Appendix C1). Its equation degree was low (Table 9). The attributes which proved as the most important were: age, minL_4-7, minL_8-10, maxL_8-10, tsun_4-7, tsun_8-10, dwf_4-7, r-aver8 (radial increments of the eight fallen trees). Annual values of selected attributes together with modeled annual increments are presented in the Appendix C2, Figure C2.

The resulting polynomial equation of the model jnj3_2m was:

$$\begin{aligned}\textit{Modeled radial-growth (mm)} = \; & + -0{,}0511025526922\ \mathit{minL\_8\text{-}10} \\ & + -0{,}0291795197998\ \mathit{maxL\_8\text{-}10} \\ & + -0{,}017479975134\ \mathit{tsun\_4\text{-}7} \\ & + 0{,}0346935385853\ \mathit{tsun\_8\text{-}10} \\ & + -1{,}950606536E\text{-}05\ \mathit{tsun\_8\text{-}10}\text{\textasciicircum}2 \\ & + -2{,}01014710248\ \mathit{dwf\_4\text{-}7} \\ & + 9{,}35586778387E\text{-}05\ \mathit{minL\_4\text{-}7}\ \mathit{tsun\_4\text{-}7} \\ & + -0{,}000179339939732\ \mathit{minL\_4\text{-}7}\ \mathit{tsun\_8\text{-}10} \\ & + 6{,}45688563611E\text{-}05\ \mathit{minL\_8\text{-}10}\ \mathit{tsun\_8\text{-}10} \\ & + 3{,}06551434164E\text{-}05\ \mathit{maxL\_8\text{-}10}\ \mathit{tsun\_4\text{-}7} \\ & + 0{,}00282485442386\ \mathit{tsun\_4\text{-}7}\ \mathit{dwf\_4\text{-}7} \\ & + -0{,}00141078675225\ \mathit{tsun\_8\text{-}10}\ \mathit{dwf\_4\text{-}7} \\ & + 7{,}91071710872\end{aligned} \quad (4)$$

(minL_4-7: minimum level of the Ledava River between April and July; minL_8-10: minimum level of the Ledava River between August and October; maxL_8-10: maximum level of the Ledava River between August and October; tsun_4-7: duration of sun radiation between April and July; tsun_8-10: duration of sun radiation between August and October; dwf_4-7: number of days with white frost between April and July).

Schematic representation of the polynomial model jnj3_2m in STELLA software is presented in the Figure 29. The comparison of the average measured annual increment and radial increments predicted by the model jnj3_2m is presented in the Figure 30 (and in the Appendix C1, Table C1, first row).

Figure 31 presents the graph on changes of predicted increments when we were increasing the Ledava River levels and decreasing the duration of sun radiation. In the absence of white frost (curve 1) the optimal conditions for radial growth were at a bit less than average level of the Ledava River and at somewhat above than average sun radiation intensity. When the conditions were moving from this situation, the increments were decreasing. The decrease was especially pronounced in humid and cloudy years. The appearance of intermediate or even exceptionally high white frosts could significantly affected annual increments. However, years with numerous days of white frost were rare (Appendix C2, Figure C2).

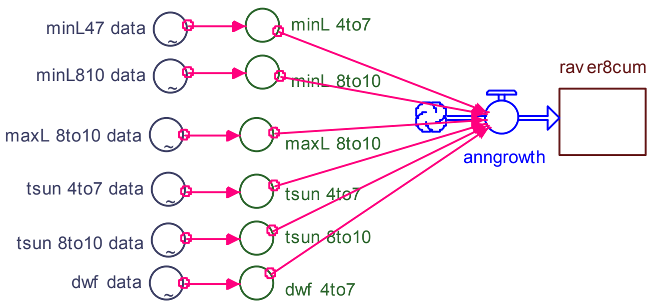


Figure 29 *A schematic representation of the selected CIPER model in the STELLA software.*

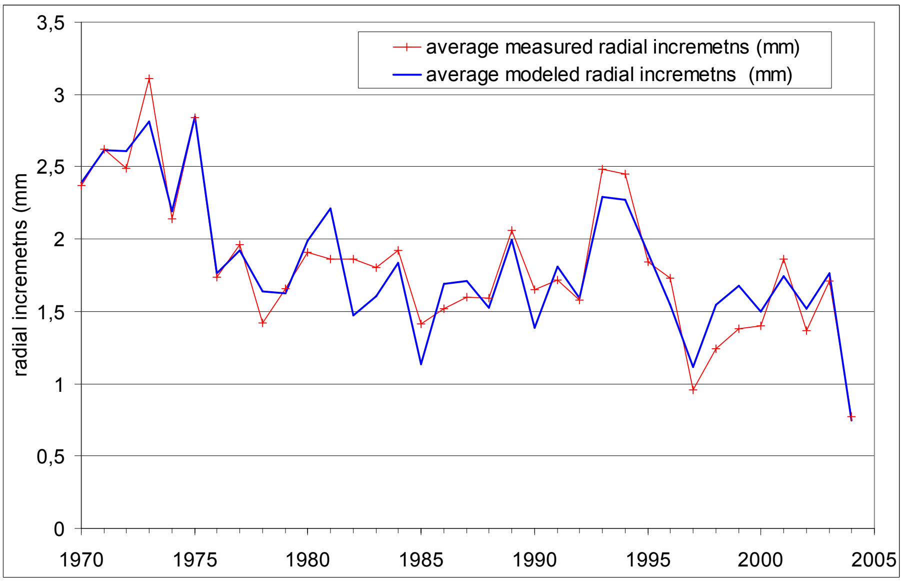


Figure 30 *The comparison of predicted (1) and measured (2) radial increments for the model jnj3_2m.*

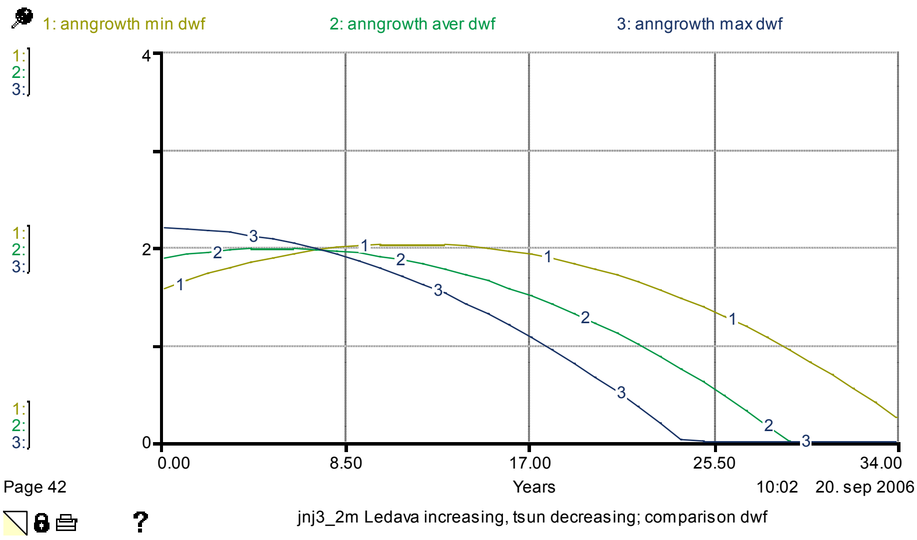
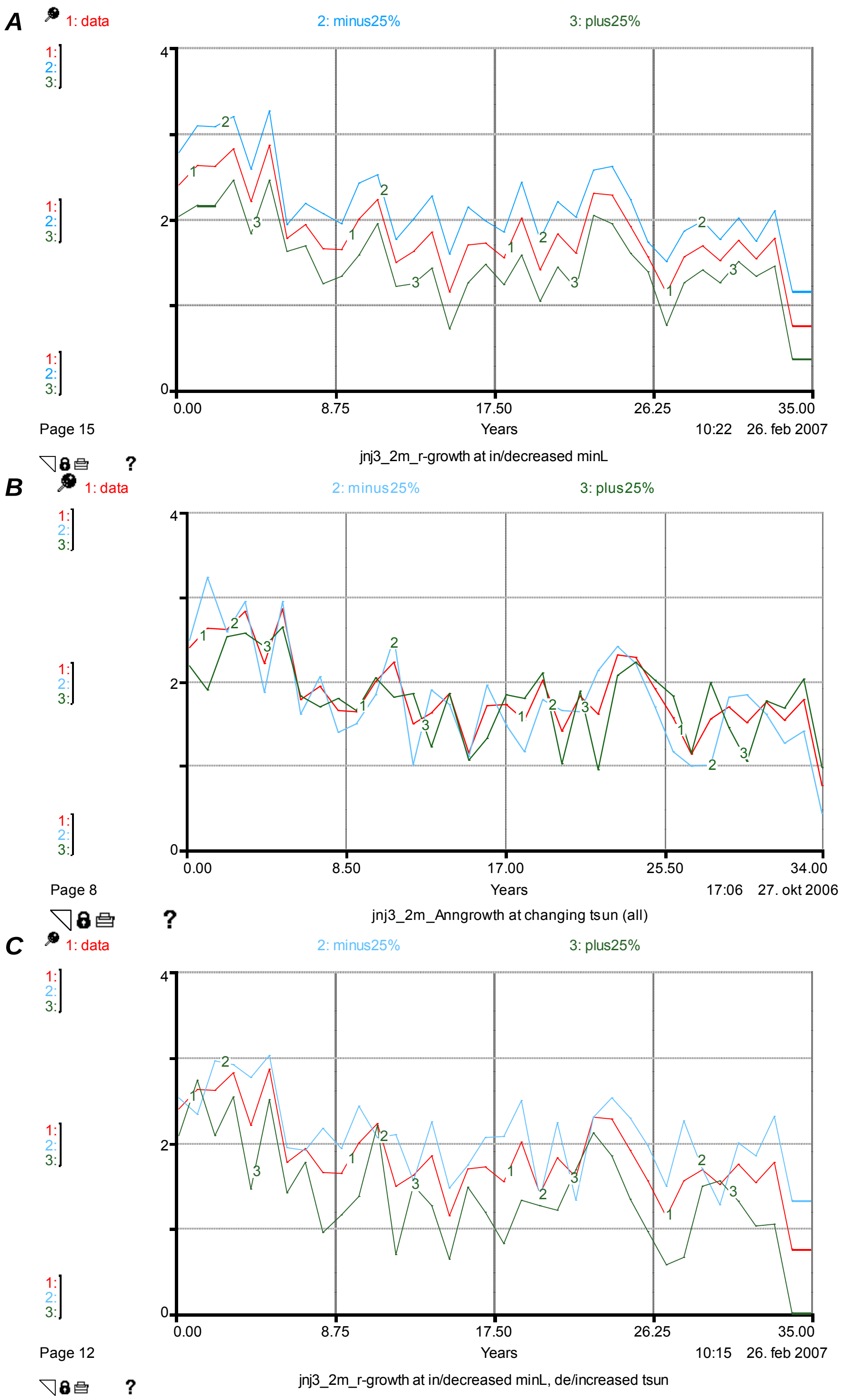


Figure 31 *Annual increments of the model jnj3_2m in the transition from dry and sunny (left) toward wet and cloudy years (right) at three levels of white frost in the spring (dwf4-7; 1: 0 days; 2: 2 days; 3: 4 days).*

The deficiency of the model jnj3_2m was that it did not account for changes in annual increments due to the age of the trees and due to thinning measures. Consequently it was not possible to run dynamic models and it was not possible to simulate responses to thinning measures.

The Figure 32 presents results of the modified sensitivity analyses of the model jnj3_2m. Some additional sensitivity analyses are presented in the Appendix C3. In sensitivity analyses we focused on the effect of increased or further decreased Ledava River level (and consequently the groundwater level) (Figure 32A; Appendix C3, Figure C3), increased or decreased duration of sun radiation (Figure 32B; Appendix C3, Figure C4), combinations of the decreased Ledava River levels and increased duration of sun radiation (drier and sunnier years) and vice versa (wet and cloudy years) (Figure 32C, D; Appendix C3, Figure C5), and the effect of increased or decreased frequency of white frost. When we tested the effect of decreased white frost in the spring (dwf4-7) on the modeled increments (Figure 32F) we did not allow that the number of days with white frost would drop below zero.



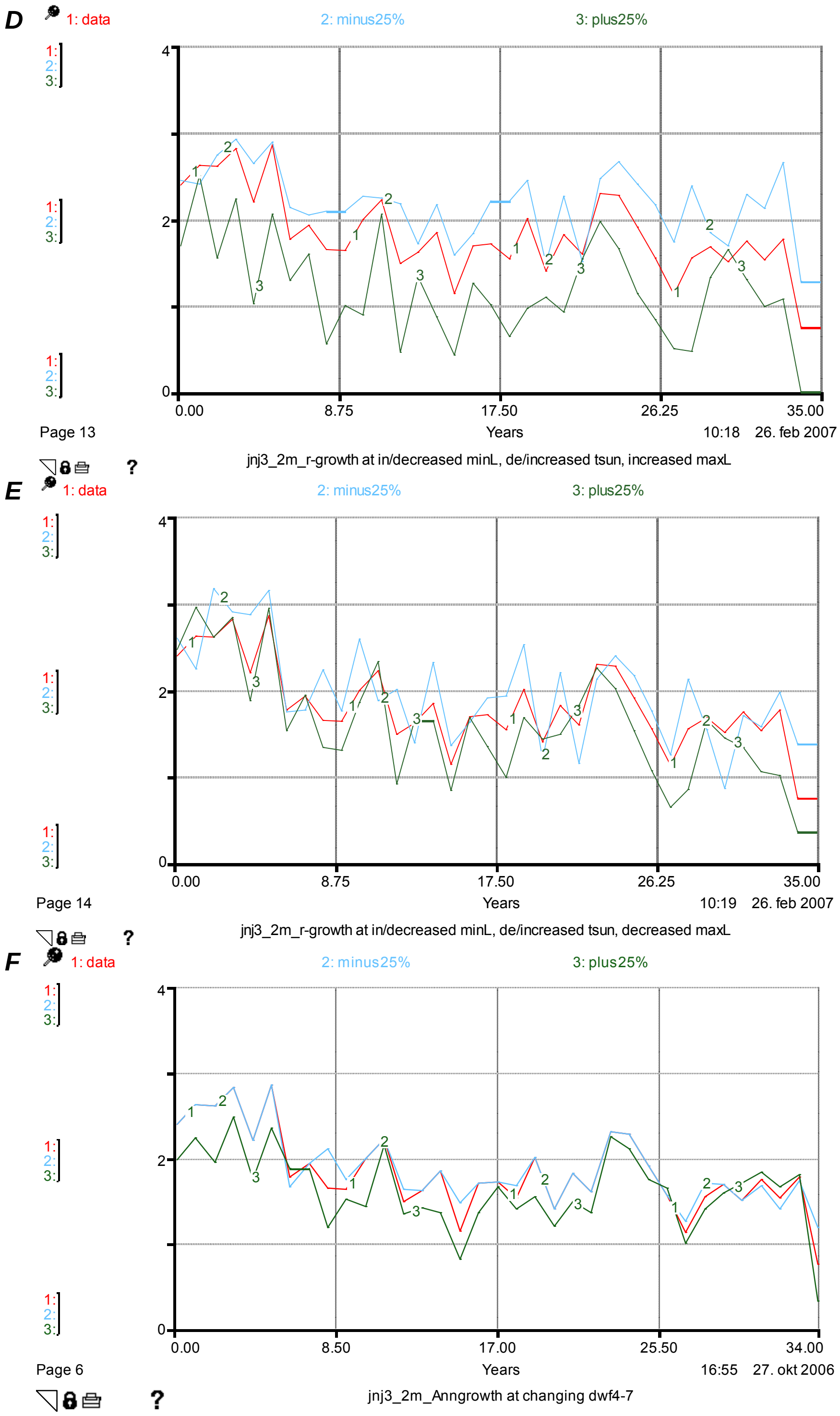


Figure 32 *The sensitivity analyses of the model jnj3_2m. Changes of predicted radial increments under original attribute values (curves 2), when attributes were increased (curves 1) or decreased (curves 3) for 25% of the observed data range.* ***A****: The minimum Ledava River levels during the whole growing season (minL_4-7, minL_8-10; cm).* ***B****: Tthe duration of sun radiation during the growing season (tsun4-7, tsun8-10; hours).* ***C****: The minimum Ledava River Levels during the growing season (minL_4-7, minL_8-10; cm) and the duration of sun radiation during the growing season (tsun4-7, tsun8-10; hours); (1: original conditions; 2: 25% increased minL and 25% decreased tsun; 3: 25% decreased minL and 25% increased tsun).* ***D****: The minimum Ledava River Levels during the growing season (minL4-7, minL8-10) and the duration of sun radiation during the growing season (tsun4-7, tsun8-10; hours) at increased maximum Ledava River levels (maxL8-10; cm); (1: original conditions; 2: 25% increased minL and maxL, 25% decreased tsun; 3: 25% decreased minL and increased maxL, 25% increased tsun).* ***E****: Equally to D, but at increased maxL8-10.* ***F****: The number of days with white frost between April and July (dwf4-7).*

Changes of radial increments due to changesin the River level indicated that radial increments decreased approximately linearly as the river levels increased. Especially linear was the response to the changed minimum Ledava River levels (Figure 32A, Appendix C3, Figure C3A, B). The response was lower when both the Ledava River levels and the duration of sun radiation (tsun) were relatively high. The response to changes in all Ledava River levels (minL4-7, minL8-10, and maxL8-10; Appendix C3, Figure C3D) was relatively linear and it was dependent also on the duration of sun radiation (tsun). The change was bigger in years with longer sun radiation and lower Ledava River levels. A graph also shows that increments were slowly decreasing in time and that influences of the River level were importantly lower in the last years. As the selected equation (4) did not consider the age of the trees, this decrease must have been a consequence of environmental attributes.

Comparison of Figure 32C, Figure 32D, and Figure 32E reveals that the increase in maxL8-10 had negative effect on radial growth in wet years, but positive effect in dry years. Whereas increased maxL8-10 further increased differences in annual increments between wet and dry years, a decrease in this attribute functioned like a buffer and it decreased differences in radial increments between dry and wet years. The effect of maxL8-10 was higher when either minL8-10 or tsun4-7 were high.

Effects of changes in the duration of sun radiation (Figure C4 A, B) were more complicated and they were strongly influenced by the appearance of white frost in the spring (dwf4-7). Increased duration of sun radiation in the first part of the growing season (tsun4-7) caused a decrease in annual increments, except if there was a white frost in the spring and if years were dry and sunny. The effect of increased duration of sun radiation in the second part of the growing season was just the opposite and it caused an increase in radial increments. The effect of increased or decreased sun radiation through the whole growing season (Figure 32B) was dependent on water conditions, the degree of sunniess, and the appearance of white frost in this year. In years with high overall sun radiation and with the low Ledava River levels, further increase in the sun radiation intensity caused a decrease in radial increments. Just the opposite was the effect of further increased sun radiation in cloudy and/or wet years.

Simultaneous changes in the value of the Ledava River level (minL4-7; e.g. increase) in the first part of the growing season and the adverse change in the duration of sun radiation (tsun4-7; e.g. decrease) were importantly affected by the appearance of white frosts and by the appearance of the high Ledava River levels (maxL8-10;Figure C5A). The appearance of white frost caused an inversion in expected increments under changing attribute values and a proportional decrease in all modeled increments. High river levels (which potentially meant that flooding took place) caused a decrease in modeled increments and they decreased differences between increments under different levels of sun radiation.

An increase in the number of days with white frost in the spring had negative effects on annual increments (Figure 32F) except under conditions of the very low Ledava River levels coupled with high duration of sun radiation. A decrease in the number of days with white frost in the spring (dwf4-7) stimulated annual increments.

The modeled increments under changing river level and inversely proportioned changing of sun radiation intensity in the second part of the growing season (minL8-10, maxL8-10, tsun 8-10; Figure C5B) were affected by white frost in a similar manner as those in the first part of the growing season but with lower intensity. The direction of changes of expected increments was inverse also in years with very high duration of sun radiation throughout the vegetation period and with relatively low River levels. The effect of changes was lower in years with high minimum levels of the Ledava River between April and July (minL4-7).

When we were simultaneously changing the Ledava River level indicators (minL4-7, minL8-10, maxL8-10) and sun radiation intensity indicators (tsun4-7, tsun8-10) (Figure C5C) there was again very important effect of white frosts and important negative effects of high sun radiation intensities when coupled with the low Ledava River levels (especially maxL8-10).

The appearance of attributes in both applied machine learning techniques and the comparative statistical data on linear regression correlation coefficients are presented in the Table 10. We can see that the agreement between regression correlation coefficient and the appearance of attributes was quite similar in WEKA and in CIPER. The agreement between both machine learning techniques was relatively good, although some other attributes within the same type were chosen (e.g. minL7 was chosen in the model tree, whereas minL4-7 was chosen in the polynomial model).

***Table 10** The comparison of attributes selected by the WEKA model (analysis 6) and these that took place in the selected CIPER model (jnj3_2m). Regression correlation coefficients (R^2) that were calculated for these attributes through linear regression (statistical analyses) are noted as well.*

Attribute	Appearance in selected model tree	Appearance in model jnj3_2m	R^2
age	✓	×	-0,62*
thinn	✓	×	-0,62*
thinn y-1	✓	×	-0,15
minL7	✓	×	-0,61*
minL4-7	×	✓	-0,665*
minL8-10	✓	✓	-0,645*
maxL8-10	×	✓	-0,15
tsun4-7	✓	✓	-0,39*
tsun8-10	×	✓	-0,25
dwf4-7	✓	✓	-0,40*

(age: the age of trees in individual years; thinn and thinn y-1: thinning before the current and before the previous growing season; minL and maxL: the minimum and maximum Ledava River levels in individual months or in periods; tsun: the duration of sun radiation; dwf4-7: the number of days with white frost. Numbers denote the successive number of the month or period to which the attribute refers).
** denotes statistical significant regression (p=0,05).*

4.2 Emergy synthesis

This chapter encloses the major results of emergy synthesis of Slovenia and results of the emergy synthesis of the stand under study. Emergy evaluation tables and changes of performance indices in time are presented.

4.2.1 Emergy evaluation of Slovenia in the year 2002

Results of the emergy synthesis of Slovenia (Appendix E) showed that the amount of emergy represented by the unit of money (Slovenian national currency was transformed to USD) was more than three times higher (5,99E+12 seJ/$) than in neighboring Italy (1,75E+12 seJ/$) (Cialani et al., 2005). This indicated that Slovenia had higher emergy use per unit of money and lower production intensity in this year. This can be explained this by the scarcity of indigenous nonrenewable resources like fuels and metal ores and quite extensive consumption of crockery (mostly limestone) which contributes less to the national economy and energetics. Moreover, Slovenian consumption of energy per capita was pretty higher than in Italy (3,64E+11 J/capita in Slovenia in 2002 and 9,12E+10 J/capita in Italy, respectively).

The other calculated performance indices for Slovenia in 2002 (Babič, 2004b) and 2000 (the data from the web-page of the Center for Environmental Policy for Slovenia[1]; in parenthesis) showed that:
- Slovenia used relatively low percentage of renewable emergy flows: 2,17% (5,5%).
- Slovenia had relatively low ratio of imported to exported flows: 0,53 (0,83).
- The ELR was 12,11 (17,0).
- The EYR was 2,56 (1,06).
- Average emergy consumption per person in Slovenia was 6,21E+16 sej (6,71E+16 sej).
- Average use per unit of area was 6,02E+12 sej/m^2/yr (6,63E+12 sej/m^2/yr).

Differences in the results of both studies could be attributed to differences in the emergy consumption in both years and to differences in the precision of the calculation.

The comparison to the other countries in the abovementioned research revealed that Slovenia can be classified as developed country with relatively high empower density (USA: 2,06E+12 sej/m^2/yr, Italy: 1,4E+13 sej/m^2/yr; Austria: 1,1E+13 sej/m^2/yr; Croatia: 2,02E+12 sej/m^2/yr), relatively high amount of emergy consumed per person (USA: 6,62E+16 sej/person/yr; Italy: 7,19E+16 sej/person/yr; Austria: 1,12E+17 sej/person/yr; Croatia: 2,56E+16 sej/person/yr) and relatively high ELR (USA: 7,29; Italy: 60,3; Austria: 31,04; Croatia: 10,04).

[1] http://sahel.ees.ufl.edu/database_resources.php?search_type=basic&country=SVN

When we compare results from different countries we must be aware that considerable differences in the applied statistical data and in their precision are possible.

4.2.2 Emergy evaluation table

In the present study emergy evaluation consists of four tables. The first table (Appendix E1) overviews physical units of emergy and matter flows and storages in individual years. The second table (Appendix E2) contains UEVs of individual flows and storages. The third table (Appendix E3) contains emergy flows in individual years. The last table (Appendix E4) contains overview on emergy of storages and summary emergy flows: local renewable (R), local non-renewable (N), purchased material and fuels (M), purchased labor and services (S), and lastly emergy of yield(s) (Y). These data were needed to calculate emergy indices (see Chapter 4.2.3).

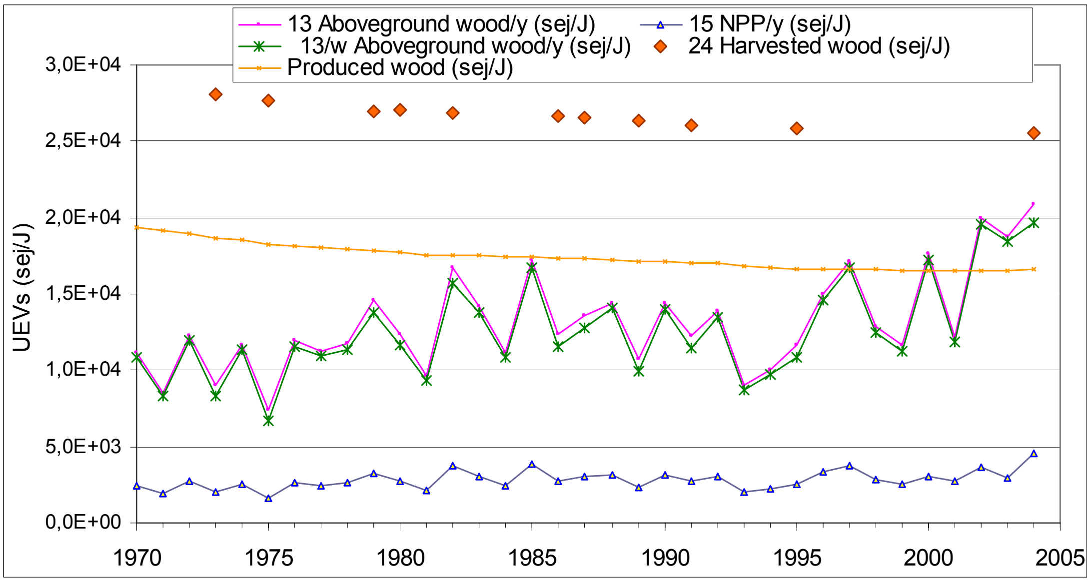


Figure 33 *The overview of UEVs of wood increments with (13 Aboveground wood/y) and without invested purchased inputs (13/w Aboveground wood/y), of the annual Net Primary Production (15 NPP/y), of annually harvested wood (24 harvested wood/y), and of the total produced aboveground wood (20 Produced wood).*

Increase in the UEV of produced wood in the last years (Figure 33) was a consequence of successive drought years.

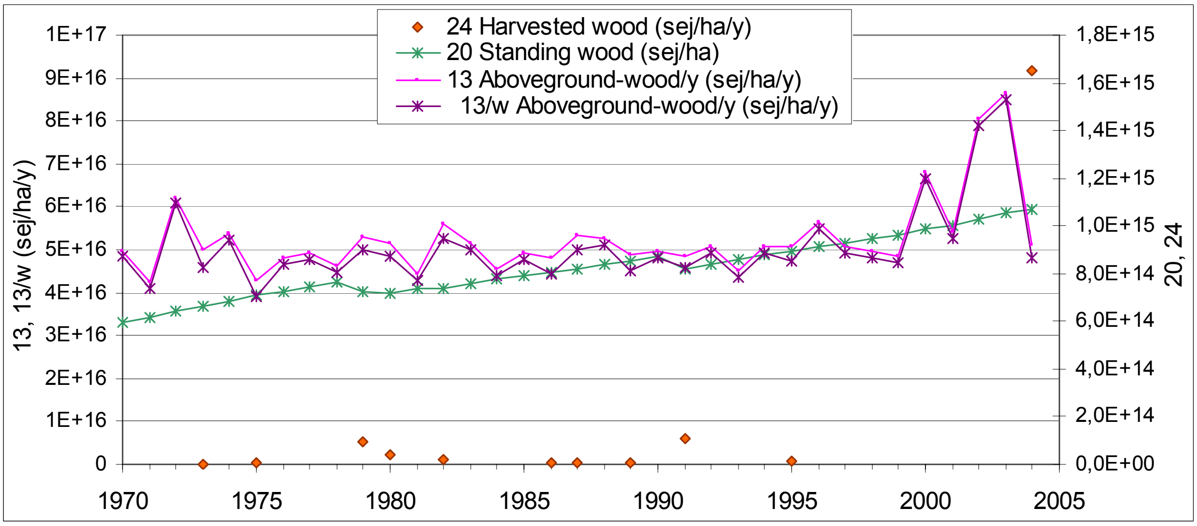


Figure 34 *The comparison of emergy invested into annual increments with (13) and without purchased inputs (13/w), into each harvest (24) and into the standing wood storages (20).*

The amount of purchased emergy invested into the standing biomass production was relatively low between 1970 and 2004 and the majority of the emergy needed for growth originated from the environment (Figure 34). However, we should not forget that purchased investments were quite high at the beginning of the production cycle due to the investment for site preparation and for planting. Emergy of storages was steadily increasing, except in years with thinning measures. The emergy of harvested wood was dependent on the amount of biomass removed. It greatly increased at the time of thinning.

4.2.3 Emergy indices

This section provides an overview on emergy indices describing the performance of the system under study in time.

Percent of renewable emergy (%R) invested into the produced wood was constantly increasing whereas %R invested into annual production was changing (Figure 35). It was lower in years with thinning measures. The percent of renewable emergy in removed wood was always significantly lower then %R of standing wood, but it was increasing in time as well. Important increase in %R was observed for the wood removed during the final clear cut.

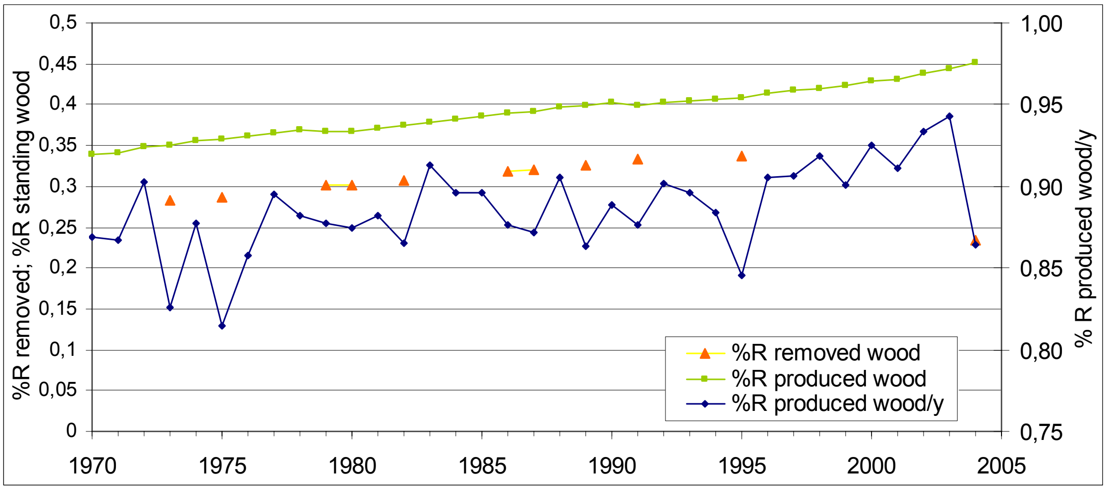


Figure 35 *The percentages of renewable emery invested into annual increments (%Rwood/y), into the standing wood and into the removed wood.*

In agreement with the %R, EYR was increasing in time as well (Figure 36). The EYR of removed wood was dependent on the amount of removed wood and it did not follow any time-dependent trends. It was low at minor thinnings due to the relatively low cost-effectiveness of such measures. The EYR of produced wood was the highest (3,15) just before the final felling, as expected.

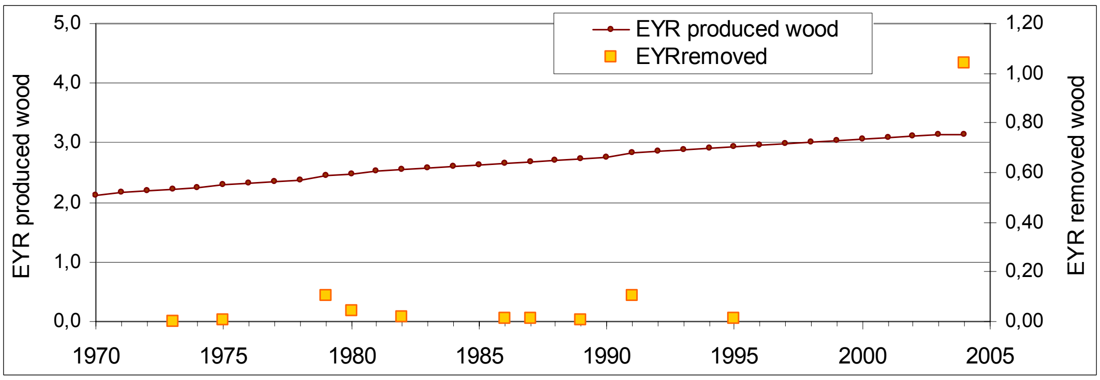


Figure 36 *Emergy Yield Ratios of produced and removed wood.*

ELR and EIR of produced wood and ELR of removed wood were constantly decreasing in time (Figure 37). Decrease in ELRs indicated decreased environmental loading of the mature stands. A decline of this index slowed down toward the end of the production cycle, approaching to the final optimal value of this index at the optimal age of the stand. In contrast to UEVs of the standing wood, this indicator was still decreasing in the last year before thinning. The actual values of ELR were always higher for the removed wood; however, the differences were not large. The only exception was the year with the final felling, when the ELR of produced wood was 0,80 (Figure 37, Figure 46) and the ELR of removed wood was 1,61.

The same was observed for the ratio between nonrenewable and renewable inputs for the removed wood. The slope of decrease of the nonrenewable to renewable ratio for produced wood was considerably lower, except the important increase in its value in the time of final felling. A final increase in this ratio was observed for produced wood.

Empower densities calculated for the standing wood were largely dependent on the annual water balance (Figure 38). Some increases were observed in years 2000, 2002 and 2003, which were characterized by droughts and our calculations revealed that important inflows of water were needed to maintain the observed water level in these years. The emergy contributed by the renewable emergy in purchased inputs was low.

The empower density of the removed wood accounted also for the purchased emergy for timber removal (Figure 38). Empower densities were higher in years with more intense thinning measures, which reflects the importance of these measures. The highest empower density took place in the last year due to the emergy invested for final felling. The empower densities calculated for unpaid investments over the whole growing season (empower density removed/y) revealed only slightly higher results than these contributed only over the growing season (empower density removed/$_{4\text{-}10}$).

If it would be possible to perform emergy synthesis over the whole production cycle, a high increase in empower densities would be observed in the time of planting and in years in which early thinning measures were performed.

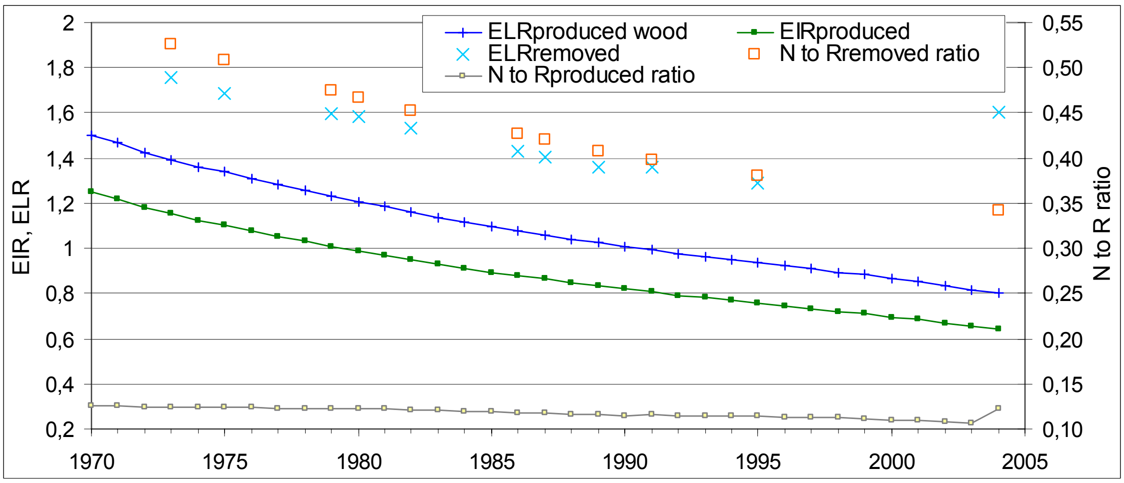


Figure 37 *The non-renewable to renewable ratio of the wood production process, the ELRs of standing and removed wood biomass and the EIRs of this process.*

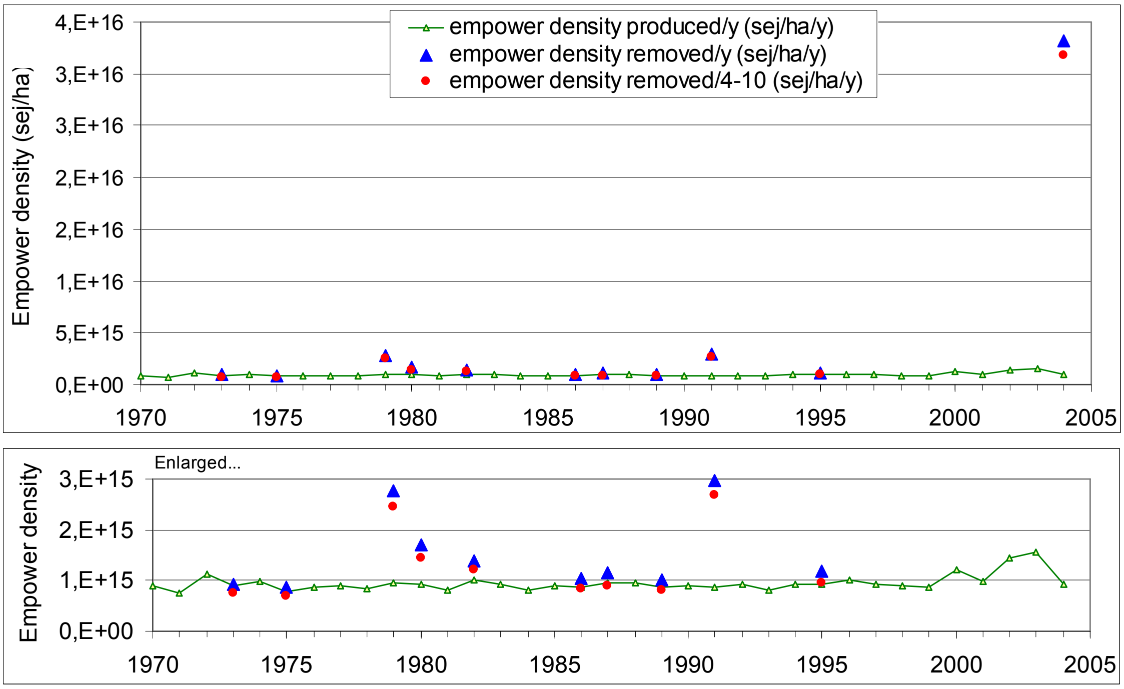


Figure 38 *The empower density of annual emergy flows invested into annual wood increments (empower density wood/y), and into the removed wood (empower density removed/y). Emergy investments into the removed wood during the growing season (empower density removed/$_{4-10}$) are marked as well. The lower graph represents the lower part of the upper graph under higher magnification.*

4.3 Ecological modeling in emergy synthesis

In the emergy model flows followed the values calculated in emergy accounting. Cumulative renewable emergy invested into the removed wood was increasing relatively linearly in time. In the last year the invested emergy highly increased due to high investments of purchased emergy for final felling and for wood removal (Figure 39). The initial value was calculated as the average emergy value accumulated over the first 35 years.

The invested nonrenewable local emergy (N) was dependent on the annual leaching from the stand and consequently it was accumulating in a relatively constant manner. The emergy of purchased goods needed for wood production ($M_{produced}$) was increasing in a similar way. Emergy of purchased goods, as well as emergy in services ($S_{produced}$), had relatively high value at the beginning of the period under study due to high investments of environmental and purchased inputs (planting and first thinning measures) that took place in the early life of the stand. In the period under study they were increasing relatively slowly, in dependence on purchased emergy invested to thinning measures. More significant in comparison to the initial value was the growth of emergy invested for the removal of the fallen wood from the stand.

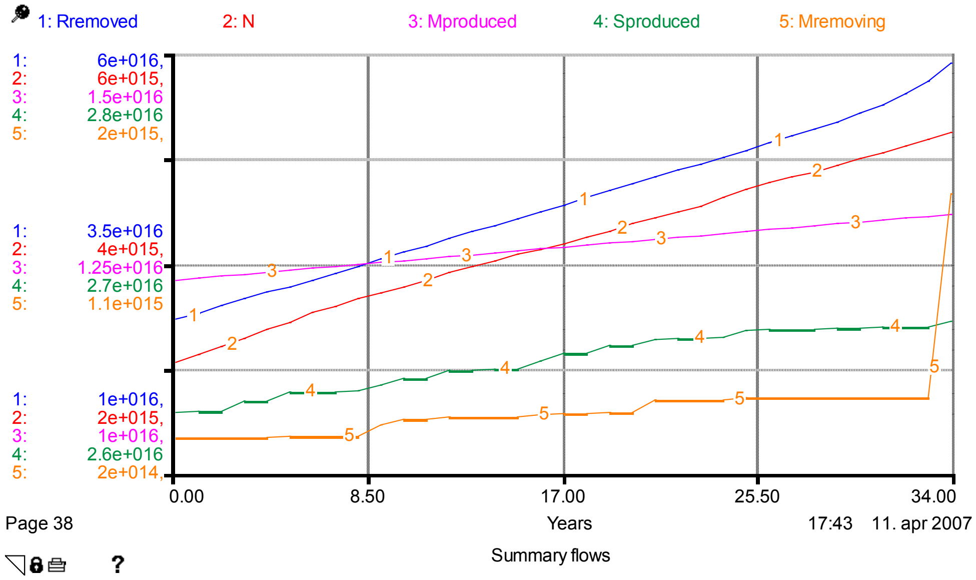


Figure 39 *Five summary flows as they were modeled under source conditions.*

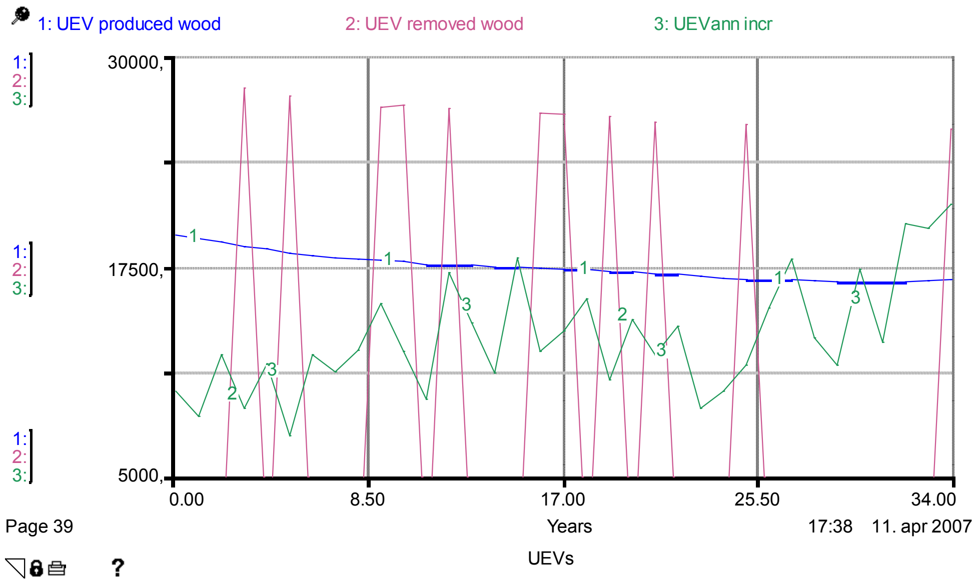


Figure 40 *UEVs calculated by the model under original conditions.*

UEVs of produced wood were constantly decreasing in time. The decrease was steeper at the beginning and it leveled in the second part of the period under study (Figure 40). UEVs somewhat increased in the last years as a consequence of very dry years with high water inflows. An increase in UEV of wood could be expected in old stands due to increased maintenance costs and decreased annual increments. In our case a significant decrease of annual increments was not observed as the stand retained relatively high production.

UEVs for removed wood were available only for years in which thinning was realized. We can see that UEVs of removed wood were decreasing in time.

UEVs of annual increments were fluctuating in dependence on the attributed emergy and in dependence on the magnitude of annual increments. In general we can observe a trend of increasing of UEVs of annual increments.

EYR and %R of produced and removed wood were increasing in time (Figure 41). The only exception was a decrease in both indices in the time of the clear-cut due to higher investments of purchased emergy needed for this measure.

The opposite was the trend in ELR and EIR. They were both decreasing until the final-cut (Figure 42). The decrease was steeper at the beginning and at the end of the period under study. In the last year there was an increase in the value of both indices calculated for the removed wood.

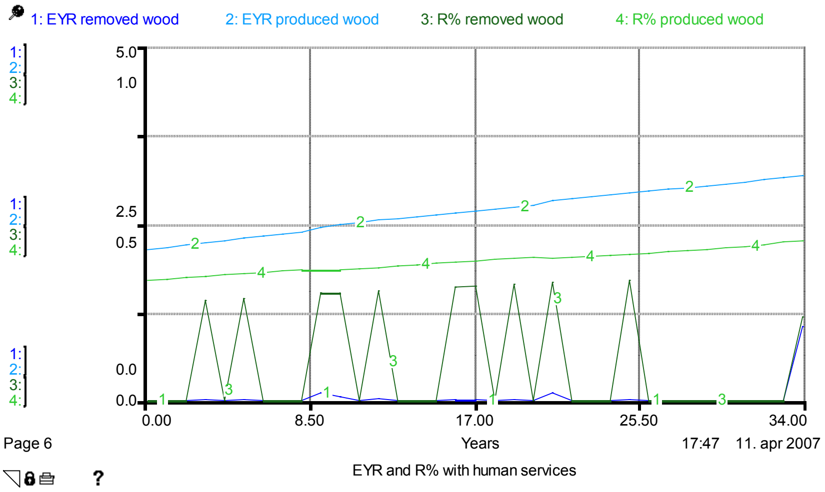


Figure 41 *EYRs and %Rs of produced and removed wood at original conditions.*

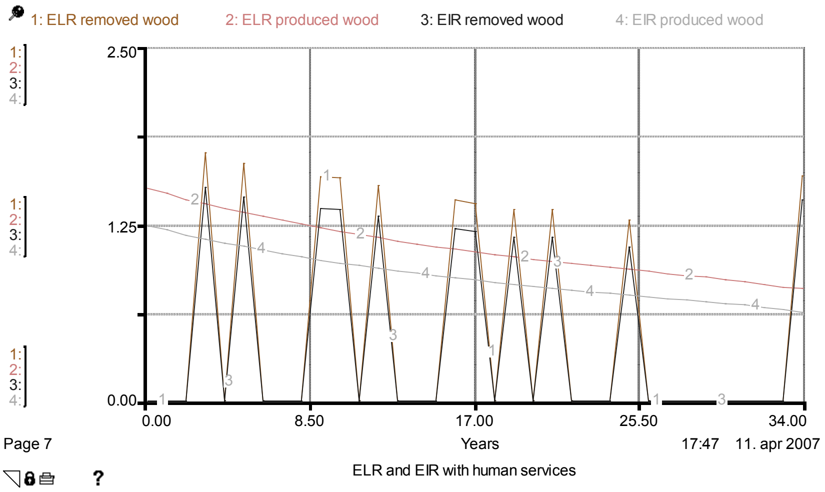


Figure 42 *ELRs and EIRs of produced and removed wood at original conditions.*

An overview on the effect of changes in the Ledava River level in combination with changes in the duration of sun radiation (Appendix H, Figures H1, H2, and H3) gave us information on changes of emergy flows and storages in the stand under three different conditions. The most interesting conclusions were:

- Both the increased and decreased Ledava River levels would importantly increase fluctuations of UEVs of annual increments, whereas the amount of emergy invested into annual increments would undergo considerably lower changes.
- Emergy of standing wood would be importantly lower at the increased Ledava River levels. The decreased Ledava River level would less affect emergy of wood in the stand.
- UEVs of the produced wood would be very different under the scenario of increased water table than under the scenario run at source conditions and at decreased water table. Under increased water table UEVs would increase in time, whereas the opposite trend would take place in the other two scenarios.

4.3.1 The sensitivity analyses

We tested the importance of several model attributes for values and trends of individual performance indices. In the majority of cases we present oscillations of performance indicators under changed individual attribute flows in the following, although several combined effects were tested as well. The attributes studied in the sensitivity analyses were:

- Purchased emergy inputs (75%, 100%, and 125% of the actually invested M and S) to simulate management alternatives with different emergy consumptions (different efficiencies).
- UEV for human work (1,1E+06, 1,1E+07 and 2,2E+07 sej/J) to represent management alternatives with different investments of manual work.
- UEV for services (1E+11, 6,2E+12 and 1,2E+13 sej/USD) to represent alternatives at different standard of living.
- The Ledava River levels (75%, 100% and 125% of the measured Ledava River levels) and the Ledava River levels in combination with the sun radiation to simulate drier and sunnier as well as wetter and cloudier years (75%, 100% and 125% of the measured Ledava River levels in combination with 125%, 100% and 75% of the measured duration of sun radiation).
- Emergy of water inflows (original conditions, annual flows increased and decreased for 5E+09 sej).
- Number of days with white frost (75%, 100% and 125% of the reported number of days with white frost).
- The nitrogen leaching intensity (40%, 63% and 86% of nitrogen in the leaf litter leached from the stand).

The following chapters present results of the sensitivity analyses performed in STELLA software. Important and illustrative graphs are presented, whereas some other results are briefly explained.

4.3.1.1 Changes in Unit Emergy Values

UEVs of produced wood were decreasing in the first decade under study. They leveled after that and they began to oscillate around the value of 1,5E+04 sej/J. This value could be regarded as an optimal UEV for this stand. The leveling indicates that the system achieved its mature stage and its optimal efficiency.

The sensitivity analysis revealed that water conditions and purchased investments were attributes with the most important influence on the performance indices including UEVs. In agreement with our expectations increased investments of purchased emergy caused proportionate increase in UEVs of produced and removed wood (Figure 43). Under 25% higher purchased investments UEVs of produced wood increased from the original value of about 1,66E+04 sej/J to 1,83E+04 sej/J in the last year before felling. Similarly, UEVs of removed wood increased from about 2,56E+04 sej/J at the last felling under source conditions to 2,95E+04 sej/J under 25% higher purchased inputs.

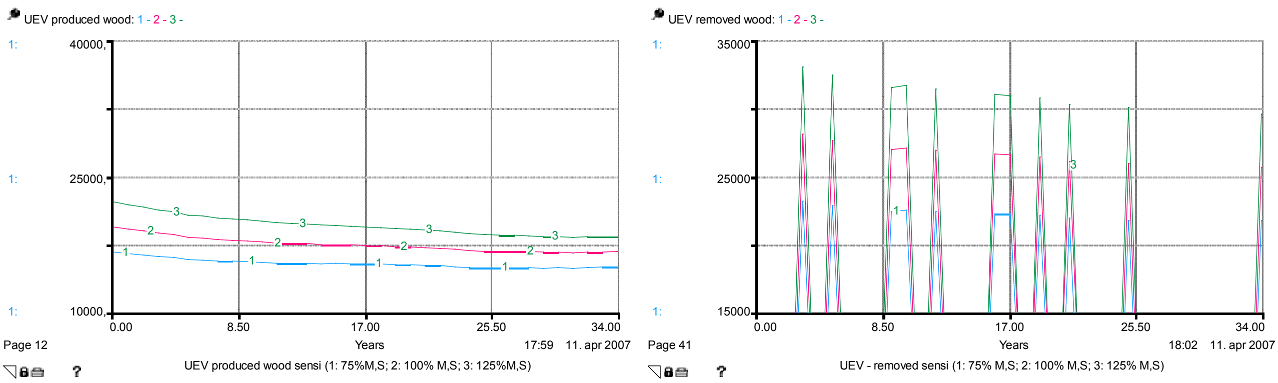


Figure 43 *A comparison of UEVs of produced wood (left) and removed wood (right) calculated at source conditions (2), at 25% higher (3) and 25% lower (1) investments of purchased emergy (M and S).*

The increased Ledava River levels caused an increase in UEVs of standing (Appendix H, Figure H4) as well as in UEVs of removed wood (the data not shown). Differences in UEVs were increasing in time because cumulative emergy flows were shown.

An increase in the Ledava River levels in combination with the decrease in sun radiation intensity (or vice versa) had somewhat different consequences (Figure 44) in comparison to the Ledava River levels alone. The increase in the Ledava River levels caused an increase in UEVs when it was combined with decreased sun radiation. The decreased Ledava River level, on the other hand, caused only slight decrease in UEVs under the increased sun radiation intensity. A reason for such a behavior was combined effect of changed radial increments on one side (e.g. decreased under the higher Ledava River level) and changed emergy flows on the other side (e.g. increased under the higher

Ledava River level). The second reason for such a behavior was a response of polynomial submodel to combined changes in both the Ledava River level and the duration of sun radiation (Figure 32C, D; Appendix C, Figure C5). Both increased and decreased sun radiation caused slight increase in UEVs (the data not shown).

The effect of changes in the emergy of inflows (precipitation and run-in) was investigated in the Appendix H (Figure H5). The decrease in water flows resulted in a relatively small decrease in the UEV of produced and removed wood, whereas an increase in inflows more importantly increased both UEVs. Outflows were always changed in parallel with inflows to avoid accumulation or complete exhaustion of water storages within the stand.

In contrast to the purchased inputs, the importance of which decreased in time (Figure 43), the effect of water flows was increasing toward the end of the production cycle (Figure 44 and Appendix H, Figures H4, and H5).

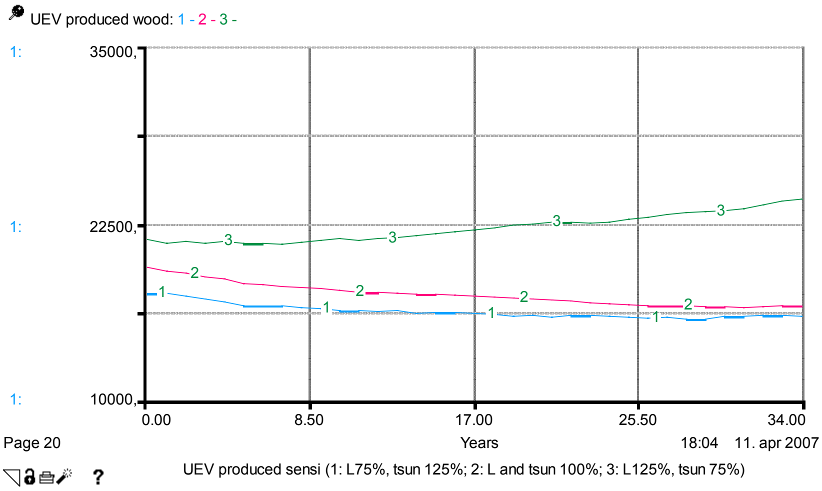


Figure 44 *The comparison of UEVs of produced wood calculated at source conditions (2) and at 25% higher Ledava River levels (L) in combination with 25% lower sun radiation (tsun) (1) and vice versa (3).*

UEVs of standing and removed wood responded in the same way in all cases; however, values of UEVs of removed wood were always higher. Whereas changes in the UEV of human work, the UEV of services, and in the emergy invested through purchased inputs caused only minor changes in the calculated UEVs of standing wood, important changes were observed in UEVs of removed wood.

Other effects of reasonable changes in source values on UEVs of standing or removed wood were discovered to be small or negligible:

- Changes in the intensity of sun radiation. On the other hand, this attribute importantly modified effects of changes in the Ledava River levels.
- Changes in the number of days with white frost or changes in the UEVs of white frost.
- Changes in the nitrogen leaching intensity and in some other properties regarding the nitrogen in the soil (the data not shown).

4.3.1.2 Changes in other performance indices

Besides on UEVs we focused on three additional performance indicators: the Emergy Loading Ratio (ELR), the Emergy Yield Ratio (EYR), and the Percent of Renewable Emergy (%R).

ELRs most strongly responded to changes in the intensity of management (invested purchased inputs; Figure 45) and to changes in the Ledava River levels. Changes in the Ledava River levels resulted in almost the same oscillations as combined changes of the Ledava River level and the duration of sun radiation (Figure 46). In agreement with expectations ELRs were increasing due to the intensified (or less effective) production. The decrease in the ELR that was observed after the Ledava River levels were increased was explained through a decrease of annual increments in years with high water table.

The third most important emergy flow with regard to the ELR was the amount of water inflows in individual years (Appendix H, Figure H6). An increase in the emergy of inflows (precipitation or ET_{oa}

and run-in of groundwater) contributed to the lower ELR, whereas decrease in these values caused a relatively low increase in the ELR.

Changes in other attributes like the duration of sun radiation, the number of days with white frost, UEVs of human wok and services, and attributes related to nitrogen flow, caused minute or small changes in ELRs.

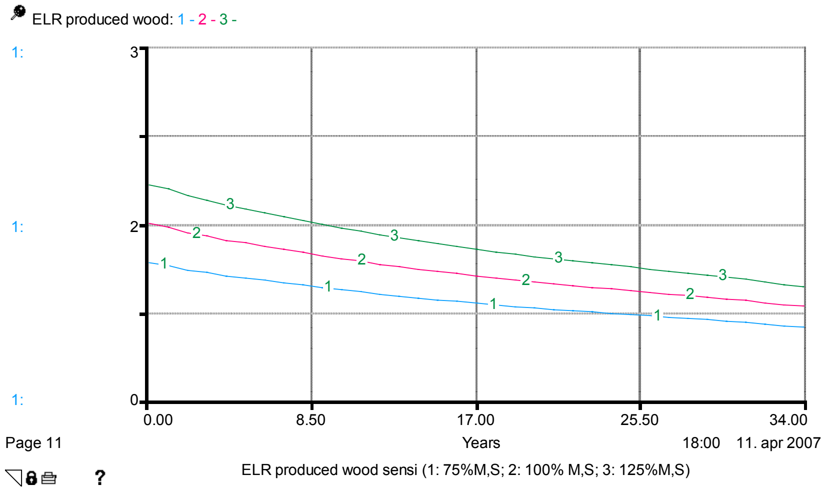


Figure 45 *The comparison of ELRs of produced wood calculated at source conditions (2) and at 25% higher (3) and 25% lower (1) investment of purchased emergy (M and S).*

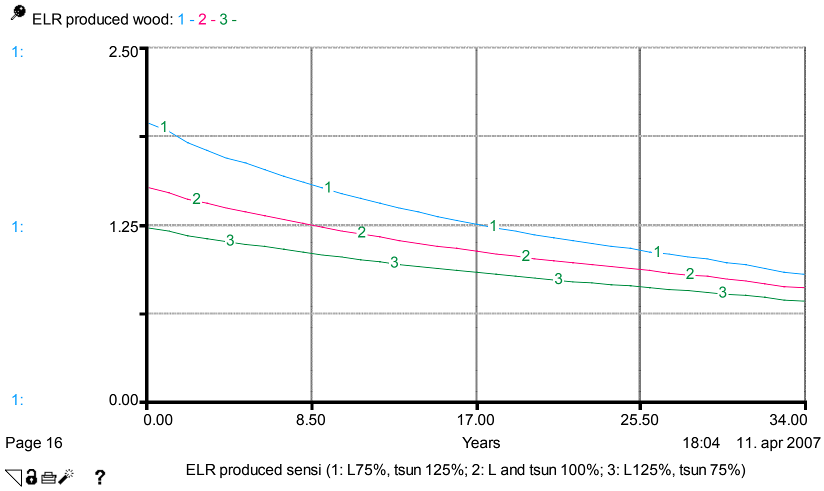


Figure 46 *The comparison of ELRs of produced wood calculated at source conditions (2) and at 25% higher Ledava River levels (L) (3) and 25% lower sun radiation (tsun) (1) and vice versa.*

EYRs ratio of produced wood responded differently in the sensitivity analysis than did EYRs of removed wood. EYRs of produced wood responded weakly to all sensitivity analyses except for changes in the purchased inputs (Appendix H, Figure H7) where it decreased at higher production intensities. Besides, we discovered that the EYR was noticeably affected by changes in the Ledava River level (especially in combination with changed duration of sun radiation; Appendix H, Figure H8), changes in water inflows, and changes in the UEV of human services. The value of the EYR of standing wood in the last year before felling was 3,17 and it decreased to 2,71 when purchased flows were increased for 25%.

Effects of changes in the Ledava River levels were different in the first and in the second half of the period under study (the data not shown). This behavior was in agreement with the results of polynomial model. Whereas EYRs linearly increased at the higher Ledava River levels in the first decade, both increases and decreases of the Ledava River levels in the last decade caused a decrease in EYRs. Changes of the Ledava River level alone were similar to combined changes of the Ledava River levels and the sun radiation, but at somewhat lower magnitude. The Ledava River levels lowered for 25% of the measured values accompanied with 25% increase in the duration of sun radiation caused a decrease in the EYR value to 3,03 in the last year before felling. Under increased Ledava River levels and the decreased duration of sun radiation the EYR of produced wood decreased to 2,86.

Increased emergy of water inflows caused relatively small increase in EYRs of produced wood.

Values of EYRs of removed wood seemed to be relatively stable over a wide range of environmental attributes and to be mostly affected by changes in invested purchased sources. They were barely affected by changes in any of the abovementioned emergy flows (purchased emergy, the Ledava River levels, and inflows). Values of EYRs for the removed wood were increasing with the amount of wood removed in individual years (the data not shown). In years without harvest EYRs cannot be calculated.

The percentage of renewable emergy (%R) invested into the produced wood was relatively prone to changes in individual attributes. This was possible due to high %R of produced wood (0,45 in the last year before felling). The most important were positive effects of the changed Ledava River level (Appendix H, Figure H10), followed by negative effects of increased purchased flows (Appendix H, Figure H9). Emergy of inflows was of lower importance, whereas the rest of attributes were more or less unimportant.

The percentage of renewable emergy (%R) invested into the removed wood was considerably lower (0,23 in the last felling). This performance index showed high sensitivity to the amount of purchased emergy (Figure 47), as well as high sensitivity to the Ledava River levels and inflows.

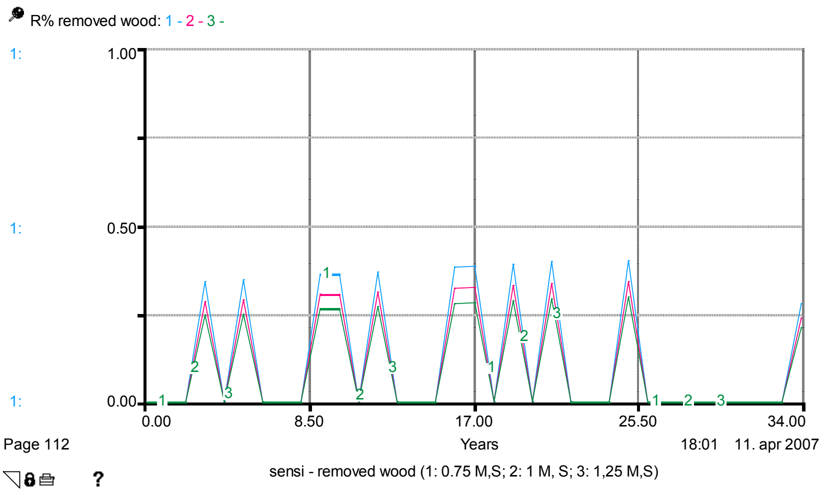


***Figure 47** The comparison of %R of the removed wood calculated at source conditions (2), at 25% higher (3) and 25% lower (1) M and S investments.*

Overall, the model predicted more drastic changes in the forest growth under increased water table and decreased duration of sun radiation than at decreased water table and increased duration of sun radiation. The model predicted the highest amount of produced wood at original scenario (420 m^3/ha or about 214.000 kg/ha at the final felling), somewhat lower amounts under scenario with the decreased groundwater level (207.000 kg/ha), and nearly half lower production (about 215 m^3/ha) under the increased water table scenario. Under original conditions the UEV of produced wood was 1,66E+04 sej/J and the total amount of emergy invested into the wood production was 5,96E+16 sej. Corresponding values under the increased Ledava River level and the decreased sun radiation scenario were 2,42E+04 sej/J and 4,44E+16 sej. Under the decreased Ledava River level and increased sun radiation scenario corresponding values were 1,59E+04 sej/J and 5,50E+16 sej, respectively.

4.3.2 Emergy and annual increments

In the next step we wanted to find out whether there is any connection between annual increments and the amount of emergy invested to the ecosystem in individual years. We determined the correlation as well as regression correlation coefficients between emergy flows or emergy indices and between measured or calculated (CIPER) annual radial increments.

Correlation coefficients and correlation regression coefficients were low for the amount of annually received emergy (Table 11). On the other hand, correlations were surprisingly high for cumulative values and for emergy indices calculated on cumulative flows. Their values were similar to values of correlations between radial increments and the Ledava River levels (Figure 21).

Table 11 *Correlation coefficients (A) and regression correlation coefficients (R^2) (B) between emergy flows or emergy indices, and between measured radial increments and radial increments predicted in the polynomial model jnj3_2m (α=0,05).*

	A		B	
	predicted	**measured**	**predicted**	**measured**
Emergy of flows and storages				
Higher of ET or precipitation (sej/ha/y)	-0,215	-0,208	0,046	0,043
19 Water in the stand (sej/ha)	-0,468	-0,514	0,219	0,264
19c Water in the stand$_{4-10\ (minL)}$ (sej/ha)	-0,603	-0,605	0,364	0,365
19c Water in the stand$_{4-10\ (averL)}$ (sej/ha)	-0,662	-0,667	0,439	0,445
Performance indices				
$R_{produced}$ (sej/ha/y)	-0,617	-0,618	0,380	0,382
$R_{produced/y\ (1970-04)}$ (sej/ha)	-0,248	-0,265	0,058	0,070
empower density $produced_{/y}$ (sej/ha/y)	-0,209	-0,218	0,048	0,044
empower density $produced_{/y/w}$ (sej/ha/y)	-0,220	-0,233	0,049	0,048
%$R_{produced/y}$	-0,463	-0,499	0,215	0,249
%$R_{produced\ wood}$	-0,642	-0,640	0,412	0,409
%$R_{/w\ wood}$	0,059	0,095	0,004	0,009
$EYR_{produced\ wood}$	0,427	-0,233	0,379	0,376
$ELR_{produced\ wood}$	0,654	0,642	0,428	0,412
$EIR_{produced}$	0,656	0,644	0,431	0,415
UEVs				
13 Standing wood $UEVs_{/y}$ (sej/J)	-0,814	-0,745	0,662	0,555
$13_{/w}$ Standing wood $UEVs_{/y}$ (sej/J)	-0,806	-0,741	0,649	0,549
19 Water in the stand UEVs (sej/J)	-0,415	-0,381	0,173	0,145
19_a Water in the $stand_{4-10}$ UEVs $_{(minL)}$ (sej/J)	-0,482	-0,500	0,232	0,250
19_b Water in the $stand_{4-10}$ UEVs $_{(averL)}$ (sej/J)	-0,264	-0,321	0,070	0,103

(minL: calculated based on the minimum Ledava River levels; averL: calculated based on the average Ledava River levels; calc const: calculated as a constant value; /w: values calculared without contributions of human work; /y: values calculated for individual years; 4-10: values calculater for individual growing seasons; 1974-2004: values calculated only over the period from 1970 to 2004).

5 DISCUSSION

5.1 Annual growth

This research has confirmed fast radial and vertical growth of trees in the first decade (Figure 7, Figure 9). In our case there was an additional period of increased radial increments observed after 1960 (Figure 7), which could be attributed either to the first thinning measures performed after the Second World War or to improved growth conditions. Unfortunately, reliable reports on management and hydrology during this time were not available.

Characteristic or pointer years became rare after 1978, which is in agreement with Čater's report (2002). Pointer years were again observed after 1996. The possible reasons for their occurrence were either improved growth conditions or new stresses. An improvement in environmental conditions in the last decades was suggested by the trend of height growth (Figure 10C), which implies that the site index shifted from below 26 toward more than 28 according to the values in stand tables (Kotar, 2003). Signs of improvement in the site index were contrary to the conviction (Nemesszeghy, 1986) that a decrease in groundwater table would cause a decrease in the mean height of stands.

The lag of the measured data on the volume of standing biomass behind the data predicted in the volume tables for black alder stands (Figure 14) at the beginning of the production period suggested that the data on early thinning measures (or the data on naturally outcompeted biomass) were insufficient or underestimated. This was also indicated by the comparison of standing and removed biomass (Figure 15). We can observe that the amount of pre-commercially removed biomass was smaller than the amount of the biomass removed in the final felling notwithstanding the fact that they aimed to equal the values predicted in forestry plans (both values around 400 m^3/ha; Kolenko, personal communication, 2004).

5.2 Feature selection

5.2.1 Statistical analyses

The minimum and average Ledava River Levels had the highest correlation with radial increments. The correlation was the highest for minimum levels at the peak of the growing season (minL5-8; r = -0,69) and across the whole growing season (averL4-10; -0,66). Among the maximum Ledava River levels (Figure 21B) the maximum level in June was the single statistically significant attribute (p = 0,05). As groundwater levels and the Ledava River levels are closely related (Levanič, 1993) this indicates the importance of both drought and flooding for the growth of these trees. Negative correlation implies negative effects of high water levels, which is contrary to the previous conviction.

Among the relatively loose correlations between the radial increments and the duration of sun radiation, the highest (simulative) correlations were prolonged periods of sun radiation at the beginning (tsun4-6; 0,41) or at the peak of the growing season (tsun4-9; 0,44). White frost at the beginning of the growing season had negatively affected radial increments (Figure 21G). This indicated that the trees could have been susceptible to white frost in the spring. On the other hand, precipitation, differences between precipitation and reference evapotranspiration, reference evapotranspiration, and temperature-related attributes, did not show significant values of regression correlation coefficients with the radial increments (Figure 21C).

Among the data that were available only on annual basis (Table 8) the age showed the highest influence on radial increments, followed by recent thinning measures.

5.2.2 Model and regression trees

Despite the generally good behavior, the selected model tree (Figure 27) often missed measured values. The annual increments decreased linearly with the increased Ledava River levels. The linearity was sustained also in very dry or very wet conditions. On the other hand, a sudden decrease in radial increments took place as the Ledava River level surpassed 96 cm (Figure 28). Decrease was in general somewhat steeper at higher ages. The highest increments were predicted under below-average river levels in both the first and in the second part of the growing season, which was contrary to our expectations. The second part of the growing season was important as it included months with the most pronounced drought. The radial increments were most negatively affected by the combination of a dry beginning and a wet conclusion of the growing season, and especially at higher ages. The trend of decreased increments at higher Ledava River levels was determined also with other model trees.

A further unexpected result was frequent negative effects of thinning on radial increments. This phenomenon could be explained by the disturbance of soil during the thinning measures, by the inability of mature trees to respond with an increased growth after thinning (Glavač, 1962; Nemesszeghy, 1986; Levanič, 1993; Kotar, 2005), or by the increased investments into branches and roots after thinning. The fourth possible explanation is that trees were not removed from the close neighborhood of the trees under study. It is also possible that thinning measures were perfectly timed and their intensity was appropriate. They were performed in the period when the annual increments would otherwise start to decline due to competition. Thereby the width of annual increments was sustained and at the same time the effects of age and the effects of thinning measures were hidden.

The effects of thinning measures were different from the thinning before the current and before the previous growing season and they depended on minimum Ledava River levels in the second part of the growing season.

The duration of sun radiation (tsun4-7) was of minor importance. However, its importance slightly increased with age. White frost (dwf4-7) was important only at high river levels in the second part of the growing season (minL8-10) up to the age of 61 (Figure 28). This could be understood as an additive effect of two stress parameters.

In general, greater changes were caused by the changes in numbers at which branching took place rather than by the changes in the attribute values themselves.

The selected model tree contained some attributes that were ranked high in the regression analyses as well (Appendix B, Table B1), whereas the others were not significant in the regression analyses.

5.2.3 Equation discovery

The selection of the best model remains an important question in machine learning tasks. In our work the reliability (RRSE) and the behavior of the model under changing individual attributes or attribute combinations were used as the most important indicators of the appropriateness of the model. Additionally, we tried to keep the degree of the equation (Table 2) as low as possible as the multiplication of different attributes is often hardly explicable.

In comparison with the other models under examination the selected one (jnj3_2m) showed a considerably higher predicting power on radial increments under study (Appendix C1, Figure C1) and a considerably higher agreement with knowledge-based expectations. The behavior of the model can be explained by means of physiological processes. The only response that could not be regarded as suitable was the reaction to frequent white frosts in the spring.

Previous studies determined the level of the Ledava River to be the most important attribute affecting growth; however, the majority of the variability in annual increments remain unexplained (Levanič, 1993). A decrease in groundwater level was reported to be the major reason for the destruction of alder forests in Europe (Pretzell et al., 1997).

5.2.3.1 Age

In contrast to the majority of other generated models (Table 2), the selected one did not consider the age of the stand. The absence of age in the model could be explained by the maturity of the stand. At this stage of life of the trees we expected an approximately linear negative trend of annual increments in time, which was also supported by the statistical analyses (Table 7). On the other hand, the model suggested that a decrease in annual increments appeared due to meteorological conditions, mostly due to the trend of increased sun radiation. This increase was observed also at other meteorological stations (ARSO). However, it would be inappropriate to add additional literature-based physiological responses of black alder trees to the existing model, as the most important responses of radial growth were included in the polynomial model.

To reliably distinguish the effect of age we would need either some samples from some younger trees from the corresponding stand or the meteorological data over a longer life-span of these trees. On the other hand, our goal was to capture the whole lifecycle of these trees in energy analysis and the focus was in the period which was vital for the quality of the product. The final emergy value of the timber could not be determined before the whole cycle had been completed. Moreover, younger trees would not give us any information about the growth trends in history, as the groundwater decreased due to subsequent hydro-meliorations.

5.2.3.2 Ledava River levels and duration of sun radiation

The decrease in increments under high Ledava River levels (and consequently high groundwater levels) was contrary to the previous conviction about the negative effects of decline in groundwater table to stand vitality (Nemesszeghy, 1986; Levanič, 1993; Smolej, 1995; Kolenko J., personal communication, 2004). It was also in disagreement with the knowledge about high degree of adaptations of this species to high groundwater levels (see Chapter 1.2.3.7).

The effect of the Ledava River level was especially important in cloudy years. The model suggested that trees sustain high groundwater levels more easily under sunny conditions. It is possible that high photosynthesis promotes the transport of oxygen to the roots (Iremonger and Kelly; 1988; Dilly et al., 2000) and that trees thereby avoid oxygen stress (Keeland and Sharitz, 1997; Iremonger and Kelly, 1988). At the same time higher photosynthesis could enable a higher transport of assimilates to the nodules and consequently a higher rate of nitrogen fixation (Wheeler, 1971; Gordon and Wheeler, 1978; Dawson and Gordon, 1979; Funk, 1990; Pizelle, 1984; Dilly et al., 2000).

Similarly, effects of oscillations in sun radiation depended on the Ledava River level. Prolonged sun radiation stimulated growth in wet years, and somewhat decreased it in dry years (Fig. 4C, D, E). It seems that moderate drought stress appeared only in very dry and sunny months.

Overall, results suggest that the stand was not endangered due to the low groundwater table. Even though extreme water conditions significantly affected radial increments, they did not endanger the stand's existence. However, care must be taken not to generalize these findings to all the stands in the area. Our results were (at least partly) in agreement with the findings of Levanič (1993), who does not gather any evidence indicating that drought could cause a decrease in radial increments in these black alder stands. He also discovers that radial increments are often low in wet years. He concludes that black alder could grow on these sites as long as it has access to groundwater.

Levanič and Kotar (1996) noted that in the majority of research plots in the neighboring stands of Črni Log the annual increments had been steadily decreasing since 1965. Only in one plot they observed a slight improvement of radial growth in the last decade before the study. It is possible that the sudden decrease in the groundwater level caused a decline of many stands in history, whereas trees slowly succeeded to physiologically and morphologically adapt to prevailing conditions after the decline and were able to take advantage of them in the period under study. Unfortunately, the data on morphological and physiological changes in the rhizosphere were not available within this period.

Trees growing in sites with oscillating groundwater level have to undergo frequent restructuring, which is energetically costly and causes frequent stress. The assertions of Levanič and Kotar (1996) are in agreement with the before mentioned physiological adaptations. The researches observe increased variability of annual radial increments after the change in the groundwater table and identify groundwater fluctuations as the major threat to these stands. This could help us to explain the trade-off between the expectations and the modeling results. A decrease in the groundwater level together with an increase in the duration of sun radiation (conditions predicted to appear in this area in the future; Sušnik, 2003; Kajfež-Bogataj, 2005) resulted in increased oscillations in annual increments in our stand as well (Figure 32C, D).

Stress that coincides with the completion of the shoot expansion has commonly a greater effect on growth than it would have later in the season (Roberts, 1983) and trees in general finish their radial growth until July (Keeland and Sharitz; 1997; Lebaube et al., 2000; Costa et al., 2003). Consequently, the high importance of environmental conditions in the second part of the growing season (August to October) seemed rather surprising. On the other hand, black alder is known to have continuous growth and it was observed to grow until September (Eschenbach, 1995; Kaelke and Dawson, 2000; Costa et al., 2003) (see Chapter 1.2.3.1). Growth in the second part of the season may be especially pronounced in trees with diffuse porous wood. September and August (sometimes also October) are also the months, when the Ledava River levels reach their minimum (ARSO; Smolej, 1995).

5.2.3.3 Thinning

Thinning measures usually cause a subsequent increase in increments of the remaining trees as they gain advantage from new resources. In the first year after thinning there could be some negative effects due to the higher investment into the canopy and roots, as well as due to the disturbance of the soil. In our case the regression analyses indicated a weak decrease of increments in the first year after thinning and insignificant increase in the following two years (Table 7). The model determined by the equation discovery tool did not include thinning into any of the generated equations. The reasons for minor importance of thinning in our stand are described in Chapter 5.2.2.

Hibbs et al. (1989) argue that thinning stimulated radial growth and decreased height growth of young red alder trees. A slight increase in radial increments following thinning is also observed in the study by Berntsen (1961 and 1962, op.cit. Hibbs et al., 1989) on 21- and 11-year-old stands.

5.2.3.4 White frost

According to the model, the frequent white frosts should stimulate radial increments at low river levels and high sun radiation intensity, whereas the increments should rapidly fall toward zero at higher river levels and lower sun radiation intensity. The insufficient number of years with more than two days of white frost (Appendix B, Figure B4A) was the most feasible reason for the unexplicable behavior of the model under high number of white frosts in the spring. The model implies that white frosts were important but not lethal.

It is known that white frosts late in the spring and early in the autumn cause significant damage in plant species in this area (Wraber, 1951) whereas no damage was reported on black alder trees (Silvicultural Chronicle, 1971-1992).

5.2.3.5 Temperature

Minor importance of temperatures for the black alder growth was discovered also in the Levanič's research (1993), whereas Horaček et al. (2003) claim that mean daily temperature, precipitation and soil water supply are important for the radial increments of the floodplain forest. Kairiukstis and Stravinskien's research (1987) carried out in the moist forests of Lithuania confirm that temperature fluctuations importantly affect annual growth.

5.2.3.6 Comparison of machine learning results

The model generated by the equation discovery was considerably more accurate in predicting annual increments than the selected model tree. It reached the measured minimum and maximum values. The largest increments were achieved in the years when the Ledava River levels were slightly below-average, with the duration of sun radiation that were somewhat above average, especially in the years without white frost.

The attributes taking place in the equations determined by the model tree and by the model determined by the equation discovery tool were quite similar. The difference was in the exclusions of the thinning measures and age in the equation discovery model and in different attributes related to the Ledava River levels taking place. Both models predicted higher radial increments at higher levels of the Ledava River.

5.3 Emergy synthesis and ecological modeling

The selected approach enabled the realization of the majority of our goals.

Firstly, the selected approach enabled the tracing of emergy flows and indices during the production cycle at different scenarios.

The emergy of water and the emergy of purchased input items contributed to the largest emergy flows to the system. Oscillations in the before mentioned attributes caused the highest oscillations in emergy indices. Whereas radial increments were found to most importantly depend on water storages, emergy flows were affected by the annual inflows or inflows during the vegetation period. Consequently, it was important to follow the emergy of water storages in emergy accounting as well, as hydrotechnical measures could cause the change in the groundwater level (and consequently change in the amount of stored water) at sustained annual amounts of water inflows and outflows.

The UEVs of produced and standing wood was in decline until 2001. The decrease was steeper in the first decade under study and almost leveled off around the age of 65. This indicated that the wood had reached its maximum value, the production efficiency was close to its optimum (Campbell, 2003a), and the predicted cycle time of 60 to 70 years was in agreement with what this emergy index would advice. The results of emergy synthesis provide a different perspective than does the common silvicultural practice, as the results are not related only to the economical or to the environmental part. Both of them were needed in the production cycle and both of them are considered in the results.

In our stand we determined the UEV of 1,660E+04 sej/J for the standing wood just before felling and UEV of 2,559E+04 sej/J for the removed wood. This shows that wood removal added about one third of emergy needed to produce wood. Additional emergy would be needed for transportation and further processing.

Similar values for UEVs of accumulated and harvested wood, as were determined in the present study, were determined also in Tilley's research (1999): 1,6E+04 sej/J and 3,0E+04 sej/J, respectively. Leofroy and Rydberg (2003) have determined the UEV of 1,88E+04 sej/J for wood produced in the tagasaste plantation and Keith (1991) determined UEV of 1,39E+04 sej/J for boles in the tropical rainforest. Slightly higher is the UEV for net timber growth and timber harvest in the research by Campbell et al., (2005b) (2,09E+04 sej/J and 6,87E+04 sej/J, respectively; 9,26E+24 sej/y global baseline) and the UEV as determined for wood growth by Odum (1996): 3,5E+04 sej/J. Still higher are the values of UEV for standing biomass in forested wetland in Florida (10,7E+04 sej/J; Bardi, 2002), and in temperate hardwoods (9E+04 to 11,7E+04 sej/J; Doherty, 1995). In these two studies the contribution of the geological structure and biodiversity have been taken into account, which was not the case in our study. On the other hand, lower values are suggested for UEV of wood in Odum et al. (2000c; 15,83E+24 sej/y baseline). Scatena et al. (2002) have determined the values between 2,8 E+04 and 12,9E+03 sej/J for Net Primary Production (NPP) in five forest types (in the present study total NPP had UEV of 4,58E+03 sej/J and aboveground NPP had UEV of 7,34E+03 sej/J).

Whereas in Tilley's (1999) and in the majority of cases in Doherty's study (1995) the UEVs of wood production increase in time, the results by Bardi (2002) support the trend observed in the present study. The decreasing trend in our case was a consequence of relatively high emergy costs invested into planting, stand preparation and care in the first years after the establishment.

The ELR and EIR of standing wood were decreasing until the final cut; however, the slope of decrease was slowly leveling. This decrease was accompanied by a constant increase of EYR and %R. Altogether, emergy indices suggest that at the time of felling economical benefits, the degree of sustainability and indirect services were still increasing along with the decline of the loading. This was the second indicator demonstrating that the determined cycle time of 60 years was appropriate and it represented the point at which economical and environmental benefits were balanced. However, the importance of biomass and multiple functions of old stands in the environment cannot be neglected. The ecosystem was becoming less and less dependent on nonrenewable sources and it developed toward a highly efficient ecosystem.

The ELR of standing wood decreased from 1,50, in the first year under study (1970), to 0,80 just before the clear cut (2004). The ELR of fallen wood was 1,61 after the final felling. Values close to one suggest a relatively well-balanced human use of the ecosystem (Brown and Ulgiati, 1997). A decreasing trend of ELR with increased rotation time is observed also in Tilley (1999).

Indicators show that relatively high costs were needed in the early years after the stand was established. If appropriate measures were taken in this period, the system was able to function in a stable and autonomous way later on. This stresses the importance of appropriate care measures.

Indices had similar trends for both produced and removed wood, notwithstanding different values due to the purchased emergy invested for wood removal.

The value of EYR of produced wood was increasing throughout the production period, despite demonstrating a trend toward leveling in the second half of the production cycle. It reached the value of 3,14 before the final felling. A similar value was calculated in the research by Tilley (1999): 3,9. In the overview of Brown and Bardi (2001) they note an EYR of 1,61 for aboveground production in a fuelwood plantation and a considerably higher value of 8,86 for aboveground production in a slash pine forestry plantation in Florida. EYR of wood removed during the final felling was 1,04.

An important goal of this study was also the identification of major threats to the system under study. The emergy indices suggest that the Ledava River levels and overall water conditions in the stand pose a major threat to the sustainability of the forest under study, followed by investment of purchased emergy and overall water conditions. Emergy performance indices were barely affected by the changes caused by duration of sun radiation alone. Negligible changes occurred due to the changes in the number of days with white frost or due to the changes in the UEV of the number of days with white frost.

To realize another goal of the research we searched for a correlation between annual radial increments, as indicators of forest function, and emergy invested into the system in individual years. We expected that the amount of annual emergy inflows would have a distinct effect on annual radial increments. However, the results of the regression and the correlation analyses revealed insignificant coincidence. This was expected as soon as the results of machine learning methods were investigated and it was discovered that the system functioned optimally at intermediate conditions. The annual radial increments decreased both in conditions of very low and of high emergy investments. This was completely in agreement with what Empower Principle would suggest. The system adapted to average conditions in the stand and all important declines from these conditions posed a threat to this system. At the same time plants were able to function in a relatively unchanged way under a range of conditions, as long as stress was not present.

A further result, which was in agreement with the predictions of the Empower Principle, was the high correlation between the annual increments and the UEVs of the annual increments. Although this result was affected by the calculation methodology (the UEV of the annual increment was dependent on the amount of the biomass produced in this year), the strength of this correlation was somewhat surprising. Such a high correlation could support the definition of UEV as an indicator of process efficiency (Bastianoni et al., 2001; Ulgiati et al., 2005; Raguei et al., 2005).

Despite the fact that we did not succeed in building a wholly dynamic model, the modeling approach enabled the combination of the ecological modeling and the emergy synthesis within a single model. This approach offers several advantages and possibilities in emergy synthesis validation and it may present an important approach toward further development of emergy synthesis. The sensitivity analyses of the emergy model proved to be a useful tool in testing changes in emergy flows under several different management scenarios and under different possible changes in the environment, in the economy, and in society. It helped us to determine the attributes and attribute combinations that were the most critical for the forest prosperity. The modeling approach accelerated the comparisons of different ecosystems, the comparison of emergy syntheses performed at different global baselines, and to a certain extent also the comparisons of different scales of research.

In our approach validation was performed through the comparison of the modeled and measured values. This approach enabled only the validation of the model in the given stand under given environmental and management conditions. The data on annual increments and environmental conditions from other stands would assure a complete validation of the model and the modeling of radial growth over the whole production cycle. Similarly, additional researches would improve the simulations of annual distribution of the biomass into separate plant organs and the reliability of modeled water flows and nitrogen cycle in the stand under study. However, these tasks were beyond the scope of this research.

We can conclude that the ecosystem under study was adapted to the local conditions. It developed in agreement with the Maximum Empower Principle and with maximum use of available renewable and nonrenewable resources. Additionally, it minimized loses in the long run. Consequently, optimal growth and minimum losses were achieved under the prevailing conditions. Large or frequent changes in emergy flows were expected to cause important fluctuations in the ecosystem function and in its stability.

5.3.1 Further possible advantages of the combined machine learning - emergy approach

There are several possibilities which could give our model more dynamic properties and which would link some of its elements, which were not interdependent in the present version. However, to determine each of these connections additional researches would be needed, which was beyond the scope of this research. An example of further examination is the cycle of nitrogen in the stand. We built a model on nitrogen cycling in the stand to simulate the process of nitrogen fixation and its leaching from the stand in emergy terms. Several different sensitivity analyses were run to visualize nitrogen cycling under different conditions. However, due to the lack of data about these processes in the stand under study in history, due to the lack of knowledge and contradict data in the literature about the effects of environmental parameters on the process of nitrogen fixation, we used this model as an illustrative tool that could become very useful when further developed.

The dendrochronology-based approach can be useful in solving several different questions in emergy synthesis. An example of such a question is the dilemma, i.e. what amount of the purchased emergy for thinning should be attributed only to the remaining standing wood. The low effect of thinning measures on annual increments suggested that the before mentioned amount should be low in this stand as well. The data on environmental function could be used as an important guidance and reference point in emergy synthesis. Similar approaches could be used in studies to distinguish between the amount of emergy which should be regarded as a split from the amount of emergy which should be regarded as a coproduct.

The modeling approach could be advantageously used also in emergy approaches that distinguish between different levels of system organization. Studies performed on different levels of organization cannot be compared directly (Campbell et al., 2005a,b). The modeling approach enables the use of the sub-model structure and consequently the comparison of results of individual levels. Campbell et al. (2005a) have divided the systems into four-levels: the level of geobiosphere, the level of ecosystems and biomes, the level of economy, and the level of society. The second possible partition would be in distinguishing three types of flows: energy, matter, and information (e.g. knowledge, genetic information, diversity, form, culture).

6 CONCLUSION

The interdisciplinary approach, which was applied in this research, resulted in novel insights and interesting conclusions about both ecosystem function and emergy synthesis. Both methods revealed some differences in the importance of individual attributes. Besides, emergy synthesis enabled important insights into the changes of sustainability of the wood production process in time and under different management and environmental conditions.

An extensive set of applied attributes assured high reliability of determination of parameters with potential effect on radial increments. It also offered an insight into the periods in which environmental attributes had the highest effects on radial growth. On the basis of the selected data it was possible to construct the temporary dynamic model of radial increments, whereas they did not enable the detailed modeling of water flows and nitrogen cycle within the stand.

Ecological modeling enabled compatibility of machine learning and emergy synthesis. The combined approach enabled an evident review of results, fast and clear simulations, and sensitivity analyses. Moreover, it revealed very important insights into the importance of emergy flows and their changes for ecosystem function and for the sustainability of the process. Overall, the selected approach represents a novel approach to systems ecology with high potential for further research work.

The selected approach enabled the fulfillment of the majority of our goals, as they were noted in the Chapter 1.3:

- *To determine environmental and management attributes that most importantly determine radial increments in the system under study and to calculate their contribution to the emergy received by the system*.

Radial increments were most importantly affected by extreme water and sun radiation conditions during the current growing season. In contrast to the expectations, the most negative were the effects of wet and cloudy growing seasons followed by dry and sunny growing seasons. Trees easier sustained flooding under sunny conditions than under cloudy conditions. Radial increments depended also on oscillations of the groundwater level during the growing season. A higher oscillation of the groundwater resulted in increased oscillations of radial increments.

Whereas water conditions importantly affected both radial increments and emergy flows and storages in the ecosystem in individual years, the duration of sun radiation caused only insignificant changes. Simultaneous changes of both attributes at the same time resulted in the highest changes of both emergy flows and radial increments.

The second attribute that affected annual increments, but not emergy flows, was the number of days with white frost in the spring. On the other hand, thinning measures did not affect radial increments in the mature forest, but they importantly affected emergy flows and emergy indices in the stand due to the changes in the amount of invested purchased emergy.

- *To build a model that will enable simulations and sensitivity analyses of energy along with emergy flows under different environmental and management conditions over the whole production cycle.*

We constructed a model which enabled simulations of radial increments under changing meteorological and hydrological conditions. In our approach, algorithms for equation discovery proved more useful than algorithms for discovery of model and regression trees. The generated polynomial submodel showed a high degree of agreement with the measured data and it offered interesting insights into ecosystem function. As the equation discovery algorithm did not determine that age and thinning measures would importantly affect radial increments, it was not possible to construct a dynamic model. We constructed the temporal dynamic model which explained temporal changes through changes in environmental conditions.

Due to the limited availability of meteorological, hydrological and management data we were not able to simulate the growth over the whole production cycle. The constructed model simulated the radial increments of the mature stand (35- to 69-year-old).

The combined growth modeling and emergy synthesis modeling approaches enabled sensitivity analyses of individual flows and flow combinations, sensitivity analysess of the applied rules and assumptions, and analyses of trends. The available data enabled limited verification and validation. Extended availability of the data on environmental conditions in the early period of stand development and the data on radial increments in stands with somewhat different depth of groundwater level would assure complete verification and further development toward the dynamic modeling.

- *To present changes in emergy performance indices during the production cycle.*

The emergy indices showed that the efficiency and sustainability of the process, as well as the percentage of environmental services invested into the process, were increasing in time. Their values were slowly leveling after the age of 60 years. The environmental loading was declining in time, approaching its final value after the age of 60 years.

Relatively high investments of emergy needed for stand establishment and early care resulted in ever increasing stand stability and sustainability during the mature period.

- *To identify attributes that present the major threat to the system under study.*

Increased oscillations of groundwater level as well as distinctly wet years coupled with insufficient intensity of sun radiation were identified as major threats to the function of this ecosystem. This was especially pronounced when impacts of frequent late white frosts in the spring were added.

It seems that the trees were well adapted to the prevailing conditions. Results suggest that the trees in this stand experienced stress at high groundwater tables, whereas previous reports (Nemesszeghy, 1986) suggest that trees experienced stress during low groundwater tables before hydrotechnical measures.

- *To define guidelines for the management with the highest possible degree of sustainability.*

Sustainability of the production process was importantly affected by the amount of invested purchased emergy. As the purchased emergy presents high emergy costs to this system and they highly affect its sustainability, care must be taken to apply these measures cautiously and suitably. The overview of the process revealed that improvements in the management efficiency (amount of emergy invested per unit of work done) were the major attribute that could be optimized in the future. The high initial emergy cost also rose attention to the emergy required to establish a stand and for early cultivation. However, the self-dependent function, increasing sustainability and the decline of environmental loading of mature forest suggested that investments during early ages resulted in a stable ecosystem later on. This indicated that these measures were of high importance for a subsequent development of the stand.

Emergy indices suggested the appropriateness of the present length of the rotation cycle.

- *To search for correlations between the magnitude of annual emergy inflows and annual radial increments.*

In this research we did not find any correlation between radial increments and annual emergy inflows. The results rejected our expectations that higher emergy inflows would result in larger annual increments. An important finding of this research was that an optimal amount of (unpaid) emergy inflows exists, which causes the largest radial increments. This finding supports the correctness of the Maximum Empower Principle: the ecosystem function takes maximum advantage at prevailing conditions.

- *To enable other improvements of modeling-based emergy accounting (see Chapter 1.2.2.1).*

The selected approach offered an important advantage to emergy synthesis including flexibility, evidence, the possibilities to compare different emergy studies, the adaptability in calculation of UEVs, and, perhaps the most important, the possibility to validate emergy synthesis through sensitivity analyses and through comparisons with indicators of (eco)system function. The modeling approach also accelerated comparisons and simulations of different process alternatives (e.g. emergy approaches done in somewhat different way, at a bit different level of complexity, based on different baseline, etc.).

A further advantage of the modeling approach is that it enables the tracing of individual flows. In this way we can trace the amount of flow regarded as coproduct, and we distinguish it from the amount, which is regarded as a split. The analyses of indicators of environmental functions, like radial increments, serve as indicators on which amount of the emergy affected the ecosystem function, i.e. they offer new approach for distinguishing between splits and coproducts.

SUMMARY

The mature black alder (*Alnus glutinosa* (L.) Gaertn.) stand within a floodplain area in South-Eastern Slovenia was studied to investigate the relation between emergy flows and ecosystem function and to determine the most important attributes affecting annual growth. An explicitly interdisciplinary approach was applied including dendrochronology, statistical methods, machine learning, ecological modeling, and emergy synthesis.

The researched black stand was characterized as a highly productive, homogenous, even-aged stand with the relatively high groundwater level. It reached the age of 69 years in 2004 and was cut down during the winter 2004/05. Before felling we performed measurements needed for stand characterization.

The study continued with the dendrochronological study of eight black alder trees. A set of 333 attributes including monthly and decadal meteorological, hydrological and management data was included in the research. These data were available over the period of 35 years before the stand was cut down. In the first step a linear regression was conducted to decrease the number of attributes with potential influence on radial increments.

The selected attributes were processed with machine learning algorithms to determine the model that would most reliably describe annual radial increments of the studied trees under changing environmental and management conditions. We applied data mining algorithms that are able to generate model and regression trees, and a polynomial equation discovery algorithm CIPER. Among several models studied, a polynomial model with the highest correlation and with the highest explanatory power was selected for further work. The most important environmental attributes that controlled the results of this model were the minimum levels of the Ledava River during the growing season, the maximum level of the Ledava River during the late summer and autumn, the duration of sun radiation during the growing season, and the number of days with white frost in the late spring (in April or later). Previous researches showed that the level of groundwater in this ecosystem is closely related to the level of the Ledava River (Levanič, 1993).

The selected model predicted that a decrease in the observed minimum groundwater level results in increased oscillations of annual increments, whereas an increase in groundwater level would cause a decrease in annual increments. Besides, it was discovered that high oscillations of groundwater level during the year would increase oscillations of annual increments. Age and management-related attributes were not found to have significant effect on annual increments in the mature stand. The model revealed that radial increments would be the lowest in the years with high groundwater levels and low duration of sun radiation. Growth would decrease also in the years with very low groundwater level and high duration of sun radiation during the growing season.

Machine learning tools proved to be very appropriate in ecological analyses. The weak point of the generated polynomial model was that it did not capture the effects of ageing and the effects of thinning operations and consequently it was not possible to construct a dynamic model. The absence of the effect of ageing was most likely a consequence of the limited availability of attribute values in history, which disabled the study of radial increments in the first 34 years after stand establishment. We were able to construct the temporal dynamic model on radial and volume increments of mature black alder trees in the studies conditions. Further work would be needed to enable the modeling of growth over the whole life cycle as well as to reliably model the distribution of nutrients between different organs in individual years and nitrogen cycle in the stand under study.

The selected polynomial model was incorporated into modeling-based emergy synthesis of the stand under study. This approach enabled sensitivity analyses and several simulations of emergy flows and indices. It enabled a simultaneous tracing of changes in radial increments and changes in emergy indices in each simulation run and the following of their changes in time. Besides this, it was possible to determine the importance of the assumptions made during the modeling.

The emergy synthesis showed that the sustainability and the yield of the process were increasing in time. Performance indices showed a trend to level off at the end of the production cycle, indicating that the length of 60 to 70 years was appropriate from the environmental point of view. This was close to the rotation period of 55 to 60 years proposed in Forest Management Plans.

The decline of the trend of Unit Emergy Values (UEVs) in time was in contrary with the findings of Tilley (1999). In our case the declining trend of this emergy index was a consequence of relatively high emergy investments needed to establish a stand and relatively low investments after that. However, the stable ecosystem function and its increasing sustainability indicated that investments for early cultivation resulted in a stable structure and function of the mature ecosystem.

The combination of ecological modeling and emergy synthesis introduced several possibilities including sensitivity analyses, simulations and comparisons. This approach enabled the identification of the most important emergy flows and the identification of crucial assumptions. The modeling approach enabled the validation and (at least partly) verification of emergy synthesis. To enable a complete validation of predicted radial increments, the data on radial increments in some other stands or in somewhat different environmental conditions would be needed.

POVZETEK

V raziskavi smo preučevali gozd črne jelše (Alnus glutinosa (L.) Gaertn.) na poplavnih ravnicah severovzhodne Slovenije. Namena raziskave sta bila preučiti povezavo med emergijskimi tokovi in funkcijo ekosistema ter določitev atributov, ki najpomembneje vplivajo na velikost letnih prirastkov. Pristop k raziskavi je bil izrazito interdisciplinaren. Uporabili smo metode dendrokronologije, statistike, strojnega učenja in emergijske sinteze.

Preučevan sestoj črne jelše označujejo visoka produktivnost, homogena zgradba, enotna starost dreves ter relativno visok nivo podtalnice. V letu 2004 je bil sestoj star 69 let, s čimer je dosegel sečno zrelost in bil v zimi 2004/2005 posekan. Še pred posekom smo izvedli meritve potrebne za karakterizacijo sestoja.

Raziskavo smo nadaljevali z dendrokronološko analizo osmih dreves. V raziskavo smo vključili 333 mesečnih in obdobnih meteoroloških in hidroloških atributov ter atributov, ki so opisovali gospodarjenje s sestojem. Na voljo smo imeli atribute za obdobje zadnjih 35ih let pred posekom. V samem začetku raziskave smo s pomočjo linearne regresije omejili nabor atributov, ki potencialno vplivajo na velikost radialnih prirastkov preučevanih dreves.

Izbrani atributi so bili podvrženi obdelavi z metodami strojnega učenja. Namen tega dela raziskave je bil pridobiti in izbrati najbolj primeren in najbolj zanesljiv model letnega debelinskega priraščanja preučevanih dreves pod spremenljivimi okoljskimi dejavniki in pri spremenljivih načinih gospodarjenja. Uporabili smo algoritme, ki generirajo modelna in regresijska drevesa, ki ustrezajo danim podatkom, ter algoritem, ki med njimi išče ustrezne polinomske enačbe. Med številnimi preučevanimi modeli smo za nadaljnje delo izbrali polinomski model, ki je izkazoval najvišje korelacije z izmerjenimi podatki in je bil najbolj v skladu z obstoječim znanjem o fiziologiji jelše. Na obnašanje in rezultate tega modela so najbolj vplivali najnižji nivoji reke Ledave tekom vegetacijske sezone ter njeni najvišji jesenski nivoji, trajanje sončnega sevanja tekom vegetacijske sezone, ter pojavljanje pozne pomladanske slane (v aprilu ali kasneje). Pretekle raziskave so pokazale, da nivo reke Ledave direktno vpliva na nivo podtalnice na tem območju (Levanič, 1993).

Izbran model napoveduje, da znižanje nivoja podtalnice povzroči povečanje nihanj v velikosti letnih debelinskih prirastkov, zvišanje nivoja podtalnice pa povzroči pomembno zmanjšanje debelinskih prirastkov. Poleg tega model napoveduje, da se nihanja letnih prirastkov še povečajo ob povečanju letnih nihanj v nivoju podtalnice (povečanju razlik med najvišjimi in najnižjimi nivoji). Starost in gospodarjenje ne vplivata na velikost letnih prirastkov v izbranem modelu. Model napoveduje najnižje prirastke v letih z visoko podtalnico in nizko količino sončnega obsevanja, pa tudi zmanjšanje rasti v izrazito suhih in sončnih letih.

Strojno učenje se je izkazalo kot zelo primerno orodje za preučevanje ekosistemov. Slabost izbranega polinomskega modela je, da ne vključuje vplivov staranja in gospodarjenja, kar je onemogočilo izgradnjo dinamičnega modela. Odsotnost vplivov starosti je bila najverjetneje posledica pomanjkanja podatkov o vrednostih okoljskih atributov v preteklosti in posledično nemogoče preučevanje vplivov okoljskih dejavnikov na rast v prvih 34-ih letih rasti sestoja.

Izgradili smo omejeno dinamični model debelinskega in volumenskega priraščanja preučevanega zrelega sestoja črne jelše. Z nadaljnjim delom bi bilo mogoče tudi modeliranje rasti proučevanega sestoje tekom njegove celotne življenjske dobe, izboljšanje zanesljivosti modeliranja razporejanja asimilatov znotraj drevesa ter izpopolnitev modeliranja kroženja dušika v preučevanem sestoju.

Izbran polinomski model smo vgradili v emergijsko sintezo preučevanega sestoja, izvedeno na osnovi modeliranja. Kombiniran pristop je omogočil izvedbo testov občutljivosti ter številnih simulacij emergijskih tokov in emergijskih indeksov. Omogočil je hkratno sledenje sprememb debelinskih prirastkov in emergijskih indeksov pri vsaki simulaciji ter sledenje njihovega spreminjanja v času. Poleg tega je omogočil tudi ugotavljanje pomena posameznih predpostavk pri izgradnji modela.

Emergijska sinteza je pokazala, da sta trajnost procesa in njegov donos naraščala s časom. Vrednosti emergijskih indeksov so proti koncu produkcijske dobe kazale trend umirjanja. To nakazuje, da je iz okoljskega vidika primerna dolžina produkcijske dobe 60-70 let. Ti podatki kažejo veliko stopnjo ujemanja s produkcijsko dobo 55-60 let, ki je predvidena v gozdnogospodarskih načrtih.

Upadajoč trend količine emergije na enoto produkta (UEVs) v času je bil v nasprotju z rezultati pretekle emergijske raziskave gozdnega sestoja (Tilley, 1999). V našem sestoju je bil padajoč trend posledica relativno visokega vlaganja emergije, ki je bilo potrebno za vzpostavitev sestoja ter za zgodnjo nego, ter relativno nizkih kasnejših vlaganj emergije, povezane s človekovim delom. Vsekakor pa stabilno funkcioniranje zrelega sestoja ter naraščajoča stopnja njegove trajnosti nakazujejo, da so zgodnja vlaganja v sestoj omogočila stabilno strukturo in funkcijo zrelega ekosistema.

Združitev ekološkega modeliranja in emergijske analize je omogočila številne nove možnosti. Med njimi so možnost izvedbe testov občutljivosti, ter hitro in nazorno izvajanje simulacij ter primerjav. Omogoča tudi določitev najpomembnejših emergijskih tokov in predpostavk. Modeliranje je omogočilo validacijo in vsaj delno verificiranje izvedene energijske sinteze. Da bi omogočili temeljito validacijo modeliranih debelinskih prirastkov bi potrebovali podatke o debelinskih prirastkih v nekaterih drugih sestojih ter sestojih, ki uspevajo v nekoliko drugačnih okoljskih razmerah.

REFERENCES

Ahas R., Jaagus J., Aasa A., 2000. The phonological calendar of Estonia and its correlation with mean air temperature. International Journal of Biometeorology, 44: 159-166.

Allen R.G., 1998. Predicting evapotranspiration demands for wetlands. ASCE Wetlands Engineering and River Restoration Conference, Denver, Colorado, March 20-29, 1998, 15 p.

Allen R.G., Jensen M.E., Wright J.L., Burman R.D., 1989. Operational estimates of reference evapotranspiration. Agronomy Journal, 81 (4): 650-662.

Amatya D.M., Skaggs R.W., Cheschier G.M., Fernandez G.P., 2000. Solar and Net Radiation for Estimating Potential Evaporation from Three Vegetation Canopies. ASAE Annual International Meeting, Technical Papers: Engineering Solutions for a New Century, 2: 2767-2786.

Andersen H.E., Hansen S., Jensen H.E., 2005. Evapotranspiration from a riparian fen wetland. Nordic Hydrology, 36 (2): 121-135.

Antonić O., Marki A., Hatić D., 1998/99. Modelling of climatic variables as a part of dendroecological study in the Repaš forest, Prekodravlje, Croatia. Hrvatski meteorološki časopis, 33/34: 39-51.

Armstrong W., Armstrong J., 2005. Stem Photosynthesis not Pressurized Ventilation is Responsible for Light-enhanced Oxygen Supply to Submerged Roots of Alder (*Alnus glutinosa*). Annals of Botany, 96: 591–612.

ARSO: the data available on the webpage of the Environmental Agency of Slovenia (http://www.arso.gov.si/).

Baar J., Bastiaans T., Van de Coevering M. A., Roelofs J. G. M., 2002. Ectomycorrhizal root development in wet Alder carr forests in response to desiccation and eutrophication. Mycorrhiza, 12 (3): 147-151.

Babič J., 2004. Emergy analysis of Slovenian national economy for the year 2002. Working paper.

Babič J., 2005. Emergy analysis of the salt production process at the Sečovlje saltpans, Slovenia. In: Emergy Synthesis 3: Theory and Applications of the Emergy Methodology. Proceedings of the Third Biennial Emergy Analysis Research Conference, January 29-31, 2004. Gainesville, Florida: 519-534.

Baker A., Hill G.F., Parsons R., 1997. Evidence for N feedback regulation of N_2 fixation in *Alnus glutinosa* L. Journal of Experimental Botany, 48 (306): 67-73.

Bakshi B., 2002. A thermodynamic framework for ecologically conscious process systems engineering. Computers and Chemical Engineering, 26: 269–282.

Baldocchi D.D., Black T.A., Curtis P.S., Falge E., Fuentes J. D., Granier A., Gu L., Knohl A., Pilegaard K., Schmid H.P., Valentini R., Wilson K., Wofsy S., Xu L., Yamamoto S., 2005. Predicting the onset of net carbon uptake by deciduous forests with soil temperature and climate data: a synthesis of FLUXNET data. International Journal of Biometeorology, 49: 377–387.

Baldocchi D.D., Wilson B.K., 2001. Modeling CO_2 and water vapor exchange of a temperate broadleaved forest across hourly to decadal time scales. Ecological Modelling, 142: 155–184.

Bardi E., 2002. Emergy evaluation of ecosystems: a basis for mitigation policy. PhD Thesis, University of Florida, USA.

Bardi E., Brown M.T., 2000. Emergy evaluation of ecosystems: a basis for environmental decision making. In: Emergy Synthesis: Theory and Applications of the Emergy Methodology. Proceedings of the First Biennial Emergy Conference, September 2-4, 1999. Gainesville, Florida: 81-100.

Bardi E., Cohen M.J., Brown M.T., 2005. A linear optimization method for computing transformities from ecosystem energy webs. In: Emergy Synthesis 3: Theory and Applications of the Emergy Methodology. Proceedings of the Third Biennial Emergy Conference, January 29-31, 2004. Gainesville, Florida: 63-74.

Bastianoni S., 1998. A definition of pollution based on thermodynamic goal function. Ecological Modelling, 113: 163-166.

Bastianoni S., Marchettini N., 1997. Emergy/exergy ratio as a measure of the level of organization of systems. Ecological Modelling, 99: 33-40.

Bastianoni S., Marchettini N., 2000. The problem of co-production in environmental accounting by emergy analysis. Ecological Modelling, 129: 187-193.

Bastianoni S., Marchettini N., Panieri M., Tiezzi E., 2001. Sustainability assessment of a farm in the Chianti area (Italy). Journal of Cleaner Production, 9: 365-373.

Bechtold J.S., Edwards R.T., Naimanr. J., 2003. Biotic versus hydrologic control over seasonal nitrate leaching in a floodplain forest. Biogeochemistry, 63: 53–71.

Bernal S., Butturini A., Nin E., Sabater F., Sabater S., 2003. Leaf Litter Dynamics and Nitrous Oxide Emission in a Mediterranean Riparian Forest: Implications for Soil Nitrogen Dynamics. Journal of Environmental Quality, 32: 191–197.

Bidlake W.R., Woodham W.M., and Lopez M.A., 1996. Evapotranspiration from areas of native vegetation in west-central Florida. US Geological Survey Water-Supply Paper, 2430. U.S. Geological Survey Open-File Report, 93-415, 35 p.

Bonal D., Barigah T.S., Granier A., Guehl J.M., 2000. Late-stage canopy tree species with extremely low δ13C and high stomatal sensitivity to seasonal soil drought in the tropical rainforest of French Guiana. Plant, Cell and Environment, 23: 445-459.

Bormann B.T., Bormann F.H., Bowden W.B., Piece R.S., Hamburg S.P., Wang D., Michael C., Snyder M.C., Li C.Y., Ingersoll R.C., 1993. Rapid N_2 fixation in pines, alder, and locust: evidence from the sandbox ecosystems study. Ecology, 74 (2): 583–598.

Bormann B.T., Gordon J.C., 1984. Stand density effects in young red alder plantations: productivity, photosynthate partitioning and nitrogen fixation. Ecology, 65 (2): 394-402.

Bouriaud O., Breda N., Le Mougedec G., Nepveu G., 2004. Modelling variability of wood density in beech as affected by ring age, radial growth and climate. Trees, 18: 264-276.

Brandt-Williams S.L., Lagerberg Fogelberg C., 2005. Nested comparative emergy assessment using milk production as a case study. In: Emergy Synthesis 3: Theory and Applications of the Emergy Methodology. Proceedings of the Third Biennial Emergy Conference, January 29-31, 2004. Gainesville, Florida: 385-400.

Brandt-Williams S., 2002. Handbook of Emergy Evaluation, Folio 4: Emergy of Florida Agriculture. Center for Environmental Policy, University of Florida, Gainesville. 40p.

Bréda N., Granier A., Aussenac G., 1995. Effects of thinning on soil and tree water relations, transpiration and growth in an oak forest (*Quercus petraea* (Matt.) Liebl.). Tree Physiology, 15: 295–306.

Brilly M., Šraj M., 2000. Osnove hidrologije (Basic Hydrology), Second edition. Faculty of Civil Engineering and Geodesy, Ljubljana, 234 p.

Brown M.T., 2003. Spatial modelling of empower and environmental loading. In: Emergy Synthesis 2: Theory and Applications of the Emergy Methodology. Proceedings of the Second Biennial Emergy Conference, September 20-22, 2001. Gainesville, Florida: 35-50.

Brown M.T., 2005. Areal empower density, unit emergy values, and emformation. Emergy Synthesis 3: Theory and Applications of the Emergy Methodology. Proceedings of the Third Biennial Emergy Conference, January 29-31, 2004. Gainesville, Florida: 1-16.

Brown M.T., Bardi E., 2001. Handbook of Emergy Evaluation, Folio 3: Emergy of Ecosystems. Center for Environmental Policy, University of Florida, Gainesville, 90p.

Brown M.T., Brandt-Williams S., Tilley D., Ulgiati S., 2000. Emergy synthesis: an introduction. In: Emergy Synthesis: Theory and Applications of the Emergy Methodology. Proceedings of the First Biennial Emergy Conference, September 2-4, 1999. Gainesville, Florida: 1-14.

Brown M.T., Buranakarn V., 2000. Emergy evaluations of material cycles and recycle options. In: Emergy Synthesis: Theory and Applications of the Emergy Methodology. Proceedings of the First Biennial Emergy Conference, September 2-4, 1999. Gainesville, Florida: 141-154.

Brown M.T., Buranakarn V., 2003. Emergy indices and ratios for sustainable material cycle and recycle options. Resources, Conservation and Recycling, 38: 1-22.

Brown M.T., Herendeen R.A., 1996. Embodied energy analysis and EMERGY analysis: a comparative view. Ecological Economics, 19: 219-235.

Brown M.T., McClanahan T.R., 1996. Emergy analysis perspectives of Thailand and Mekong River dam proposals. Ecological Modelling, 91: 105-130.

Brown M.T., Ulgiati S., 1999. Emergy evaluation of the biosphere and natural capital. Ambio, 28 (6): 486-493.

Brown M.T., Ulgiati S., 1997. Emergy based indices and ratios to evaluate sustainability: monitoring economies and technologies toward environmentally sound innovation. Ecological Engineering, 9: 51-69.

Brown M.T., Ulgiati S., 2004. Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understanding systems. Ecological Modelling, 178 (1-2): 201-213.

Brus R., 2004. Drevesne vrste na Slovenskem (Tree Species in Slovenia). Mladinska knjiga, Ljubljana, 399 p.

Brus R., 2005. Dendrologija za gozdarje (Dendrology for Foresters). Biotechnical Faculty, Department for renewable forest resources, Ljubljana, 408 p. (in Slovene).

Buchel H.B., Grosse W., 1990. Localization of the porous partition responsible for pressurized gas transport in *Alnus glutinosa* (L.) Gaertn. Tree Physiology, 6: 247–256.

Buragraaf A.J.P., Shipton W.A., 1982. Estimates of *Frankia* growth under various pH and temperature regimes. Plant and Soil, 69: 135-147.

Buranakarn V., 1998. Evaluation of Recycling and Reuse of Building Materials Using Emergy Analysis Method. PhD dissertation, University of Florida, USA, 260 p.

Buranakarn V., 2003. Emergy evaluation of building operation in Thailand. In: Emergy Synthesis 2: Theory and Applications of the Emergy Methodology. Proceedings of the Second Biennial Emergy Conference, September 20-22, 2001. Gainesville, Florida: 123-140.

Camiré C., Côté B., Brulotte S., 1991. Decomposition of roots of black alder and hybrid poplar in short-rotation plantings: Nitrogen and lignin control. Plant and Soil, 138: 123-132.

Campbell D.E., 2000. A revised solar transformity for tidal energy received by the Earth and dissipated globally: implications for emergy analysis. In: Emergy Synthesis: Theory and Applications of the Emergy Methodology. Proceedings of the First Biennial Emergy Conference, September 2-4, 1999. Gainesville, Florida: 255-264.

Campbell D.E., 2001. An energy system analysis of constraints on economic development. In: Proceedings of the Second International Workshop Advances in Energy Studies, May 23-27, 2000. Porto Venere, Italy, 175-188.

Campbell D.E., 2003a. Emergy analysis of the prehistoric global nitrogen cycle. In: Emergy Synthesis 2: Theory and Applications of the Emergy Methodology. Proceedings of the Second Biennial Emergy Conference, September 20-22, 2001. Gainesville, Florida: 221-240.

Campbell D.E., 2003b. A note on the uncertainity in estimates of transformities based on global water budgets. In: Emergy Synthesis 2: Theory and Applications of the Emergy Methodology. Proceedings of the Second Biennial Emergy Conference, September 20-22, 2001. Gainesville, Florida: 349-354.

Campbell D.E., 2005. Financial accounting methods to further develop and communicate environmental accounting using emergy. In: Emergy synthesis 3: Theory and Applications of the Emergy Methodology. Proceedings of the Third Biennial Emergy Conference, January 29-31, 2004. Gainesville, Florida: 185-198.

Campbell D.E., 2006. Global Transition to Sustainable Development. In: Proceedings of the 4th Biennial Workshop, Advances in Energy Studies, “Ecology-Energy in Latin America”. June 16-19, 2004. Campinas, SP, Brazil: 11-28.

Campbell D.E., Brandt-Williams S.L., Cai T., 2005a. Current technical problems in emergy analysis. In: Emergy Synthesis 3: Theory and Applications of the Emergy Methodology. Proceedings of the Third Biennial Emergy Conference, January 29-31, 2004. Gainesville, Florida: 143-158.

Campbell D.E., Brandt-Williams S., Meisch M.E.A., 2005b. Environmental Accounting Using Emergy: Evaluation of the State of West Virginia. U.S. Environmental Protection Agency, Office of Research and Development, 116 p.

Campbell D.E., Meisch M., Demoss T., Pomponio J., Bradley M.P., 2004. Keeping the books for environmental systems: an emergy analysis of West Virginia. Environmental Monitoring and Assessment, 94: 217-230.

Carlyle C., 1998. Relationships between nitrogen uptake, leaf area, water status and growth in an 11-year-old *Pinus radiata* plantation in response to thinning, thinning residue, and nitrogen fertilizer. Forest Ecology and Management, 108 (1-2): 41-55.

Case R.A., MacDonald G.M., 2003. Tree ring reconstructions of streamflow for three Canadian Prairie rivers. Journal of American Water Resources Association, 39 (3): 703-716.

Castellini C., Bastianoni S., Granai C., Bosco A.D., Brunetti M., 2006. Sustainability of poultry production using the emergy approach: Comparison of conventional and organic rearing systems. Agriculture, Ecosystems and Environment, 114 (2-4): 343-350.

Čater M., 2002. Vpliv svetlobe in podtalnice na naravno in umetno obnovo doba (*Quercus robur* L.) v nižinskem delu Slovenije (Effect of light and groundwater table on natural and planted seedlings of pedunculate oak (*Quercus robur* L.) in lowland parts of Slovenia). Strokovna in znanstvena dela, N^{o}120. Slovenian Forestry Institute, 115 p. (in Slovene).

Čermák J., 1998. Leaf distribution in large trees and stands of the floodplain forest in southern Moravia. Tree Physiology, 18 (11): 727-737.

Čermák J., Kučera J., Prax A., Bednářová E., Tatarinov F., Nadyezhdin V., 2001. Long-term course of transpiration in a floodplain forest in southern Moravia associated with changes of underground water table. Ekologia Bratislava, 20: 92-115.

Čermák J., Prax A., 2001. Water balance of a Southern Moravian floodplain forest under natural and modified soil water regimes and its ecological consequences. Annals of Forest Science, 58: 15-29.

Chmielewski F.M., Rötzer T., 2001. Response of tree phenology to climate change across Europe. Agricultural and Forest Meteorology, 108: 101-112.

Cialani C., Russi D., Ulgiati S., 2005. Investigating a 20-year national economic dynamics by means of emergy-based indicators. In: Emergy Synthesis 3: Theory and Applications of the Emergy Methodology. Proceedings of the Third Biennial Emergy Analysis Research Conference, January 29-31, 2004. Gainesville, Florida: 401-416.

Cleveland C.J., Kaufman R.K., Stern D.I., 2000. Aggregation and the role of energy in the economy. Ecological Economics, 32: 301-317.

Cohen M., 2003. Dynamic emergy simulation of soil genesis and techniques for estimating transformity confidence envelope. In: Emergy Synthesis 2: Theory and Applications of the Emergy Methodology. Proceedings of the Second Biennial Emergy Conference, September 20-22, 2001. Gainesville, Florida: 355-370.

Cohen M.T., Bardi E., Brown M.T., Ingwersen W.W., 2005. Emergy, transformity and network analysis of Everglades ecosystem. Emergy Synthesis 3: Theory and Applications of the Emergy Methodology. Proceedings of the Third Biennial Emergy Conference, January 29-31, 2004. Gainesville, Florida: 75-92.

Cole D.W., Compton J., VanMiegroet H., Homan P., 1990. Changes in soil properties and site productivity caused by red alder. Water and Soil Pollution, 54: 231-246.

Collins D., 2003. On rationale of the transformity method. In: Emergy Synthesis 2: Theory and Applications of the Emergy Methodology. Proceedings of the Second Biennial Emergy Conference, September 20-22, 2001. Gainesville, Florida: 171-184.

Collins D., Odum H.T., 2000. Calculating transformities with an eigenvector method. In: Emergy Synthesis: Theory and Applications of the Emergy Methodology. Proceedings of the First Biennial Emergy Conference, September 2-4, 1999. Gainesville, Florida: 265-280.

Costa A., Pereira H., Oliveira A., 2003. Variability of radial growth in cork oak adult trees under cork production. Forest Ecology and Management, 175 (1-3): 239-246.

Costanza R., Duplisea D., Kautsky U., 1998. Ecological Modeling on modeling ecological and economic systems with STELLA. Ecological Modeling, 110: 1-4.

Costanza R., Ruth M., 1998. Using Dynamic Modeling to Scope Environmental Problems and Build Consensus. Environmental Management, 22 (2): 183-195.

Costanza R., Voinov A., 2001. Modeling ecological and economic systems with STELLA: Part III. Ecological Modelling, 143: 1-7.

Costanza R., Voinov A., Boumans R., Maxwell T., Villa F., Wainger L., Voinov H., 2002. Integrated ecological economic modeling of the Patuxent River watershed, Maryland. Ecological Monographs, 72 (2): 203-231.

Côté B., Camire C., 1984. Growth, nitrogen accumulation, and symbiotic dinitrogen fixation in pure and mixed plantings of hybrid poplar and black alder. Plant and Soil, 78 (1-2): 209-220.

Côté B., Camire C., 1985. Nitrogen cycling in dense plantings of hybrid poplar and black alder. Plant and Soil, 87 (1): 195-208.

Côté B., Camire C., 1987. Tree growth and nutrient cycling in dense plantings of hybrid poplar and black alder. Canadian Journal of Forest Research, 17 (6): 516-523.

Côté B., Dawson J.O., 1986. Autumnal changes in total nitrogen, salt-extractable proteins and amino acids in leaves and adjacent bark of black alder, eastern cottonwood and white basswood. Physiologia Plantarum, 67: 102-108.

Côté B., Vogel C.S., Dawson J.O., 1989. Autumnal changes in tissue nitrogen of autumn olive, black alder and eastern cottonwood. Plant and Soil, 118 (1-2): 23-32.

Črepinšek Z., Kajfež-Bogataj L., 2005. Modeliranje fenooškega razvoja pri rastlinah (Modelling of ohenological development in plants). Acta Agriculturae Slovenica, 85 (2): 263-281 (in Slovene).

Culiberg M., Šercelj A., 1989. Forests of Prekmurje in closer and longer history. Gozdarski vestnik, 47 (5): 218-223 (in Slovene).

Cutini A., Matteucci G., Mugnozza G.S., 1998. Estimation of leaf area index with the Li-Cor LAI 2000 in deciduous forests. Forest Ecology and Management, 105: 55-65.

Dawson J.O., Funk D.T., 1981. Seasonal change in foliar nitrogen concentration of *Alnus glutinosa*. Forest Science, 27 (2): 239-243.

Dawson J.O., Funk D.T., Fitton R.R., Gertner G.Z., 1980. Seasonal changes in leaf nitrogen concentration of *Alnus glutinosa, A. rugosa and A. serrulata*. In: Garrett H.E., Cox G.S. (eds.), Central Hardwood Forest Conference III. School of Forestry, Fisheries, and Wildlife, University of Missouri, Columbia, 190-201 p.

Dawson J.O., Godon J.C., 1979. Nitrogen fixation in relation to photosynthesis in *Alnus glutinosa*. Botanical Gazette, 140: 70-75.

Dawson T.E., 1996. Determining water use by trees and forests from isotopic, energy balance and transpiration analyses: the roles of tree size and hydraulic lift. Tree Physiology, 16: 263-272.

DeBell D.S., 2006. History of research and attitudes about the biology and management of red alder. In: Deal R.L., Harrington C.A., eds., 2006. Red alder – a state of knowledge. General Technical Report PNW-GTR-669. Portland, U.S. Department of Agriculture, Pacific Northwest Research Station, 150 p.

DeBell D.S., Clendenen G.W., Harrington C.A., Zasada J.C., 1996. Tree growth and stand development in short-rotation *Populus* planting: 7-year results for two clones at three spacings. Biomass and Bioenergy, 11(4): 253-269.

Decree on determination of normatives for work in forests (Odredba o določitvi normativov za dela v gozdovih; Ur. l. RS, št. 11/99), 1999. (http://www.arhiforum.com/zakoni/Literatura-ul-11-99.htm. Accessed in December, 2006).

Dekker S.C., 2000. Modelling and monitoring forest evapotranspiration; Behaviour, concepts and parameters. PhD thesis, University of Amsterdam, 120 p.

Diaci J., 1999. Meritve sončnega sevanja v gozdu - I. Presoja metod in instrumentov (Solar radiation measurements in forest - I. evaluation of methods and instruments). Zbornik gozdarstva in lesarstva, 58: 105-138.

Diaci J., Kolar U., 2000. Umerjanje objektiva “ribje oko” za fotografijo hemisphere (Calibration of the “fish-eye” objective for hemispherical photography). Zbornik lesarstva in gozdarstva, 60: 5-25.

Diaci J., Thormann J.J., Kolar U., 1999b. Meritve sončnega sevanja v gozdu - II. Metode na osnovi projekcij hemisfere neba in krošenj (Solar radiation measurements in forest - II. Methods based on projection of hemisphere of sky and crowns). Zbornik gozdarstva in lesarstva, 60: 177-210.

Dilly O., Bach H.J., Buscot F., Eschenbach C., Kutsch W.L., Middelhoff U., Pritsch K., Munch J.C., 2000. Characteristics and energetic strategies of the rhizosphere in ecosystems of the Bornhöved Lake district. Applied Soil Ecology, 15: 201–210.

Dilly O., Blume H.P., Kappen L., Kutsch W.L., Middelhoff U., Wotzel J., Buscot F., Dittert K., Bach H.J., Mogge B., Pritsch K., Munch J.C., 1999. Microbial processes and features of the microbiota in histosols from a black alder (*Alnus glutinosa* (L.) Gaertn.) forest. Geomicrobiology Journal, 16 (1): 65-78.

Dilly O., Munch J.C., 1996. Microbial biomass content, basal respiration and encyme activities during the course of decomposition of leaf litter in black alder (*Alnus glutinosa* (L.) Moench.) forest. Soil Biology and Biochemistry, 28 (8): 1073-1081.

Dittert K., Wötzel J., Sattelmacher B., 2006. Responses of *Alnus glutinosa* to anaerobic conditions - Mechanisms and rate of oxygen flux into the roots. Plant Biology, 8 (2): 212-223.

Dittmar C., Fricke W., Elling W., 2005. Impact of late frost events on radial growth of common beech (*Fagus sylvatica* L.) in southern Germany. European Journal of Forest Research, 125 (3): 249-259.

Doherty S., Rydberg T., 2002. Ecosystem properties and principles of living systems as foundation for sustainable agriculture – Critical reviews of environmental assessment tools, key findings and questions from course process. Report Ekologiskt lantbruk, Nº 32. Center for Ecological Agriculture, Uppsala, Sweden. (http://orgprints.org/00002832/01/ekolantbruk32.pdf).

Doherty S.J., 1995. Emergy evaluations of and limits to forest production. PhD thesis, University of Florida, 214 p.

Dolch R., Tscharntke T., 2000. Defoliation of alders (*Alnus glutinosa*) affects herbivory by leaf beetles on undamaged neighbors. Oecologia, 125 (4): 504-511.

Džeroski S., 2001a. Applications of symbolic machine learning to ecological modeling. Ecological Modelling, 146: 263–273.

Džeroski S., 2001b. Data mining in a nutshell. In: Džeroski S., Lavrač N. (eds.). Relational Data Mining. Springer, Berlin, 3-27.

Džeroski S., 2002. Environmental sciences. In: Kloesgen W., Zytkow J. M. (ed.), Handbook of Data Mining and Knowledge Discovery. Oxford University Press, Oxford: 817-830.

Džeroski S., Todorovski L., Bratko I., Kompare B., Križman V., 1999. Equation discovery with ecological applications. In: Fielding A.H. (ed.). Machine learning methods for ecological applications. Kluwer Academic Publisher, Boston, p. 185-207.

Ekblad A., Lundquist P.O., Sjöström M., Huss-Danell K., 1994. Day-to-day variation in nitrogenase activity of *Alnus incana* explained by weather variables: a multivariate time series analysis. Plant, Cell and Environment, 17 (3): 319–325.

Eschenbach C., 1995. Zur Physiologie und Ekologie der Schwarzerle *Alnus glutinosa* (L.). Dissertation, Universität Kiel, 197 p.

Eschenbach C., 1996. Zur Ökophysiologie der Primärproduktion der Schwarzerle (*Alnus glutinosa* (L.) Gaertn.). Verhandlungen der Gesellschaft für Ökologie, 26: 89-95.

Eschenbach C., 1998. Modeling growth, development and architecture of Black alder trees with an object-oriented approach. In: Proceedings of the 24th Conference of the ASU. ASU Newsletter, 24: 75-85.

Eschenbach C., 2000. The effect of light acclimation of single leaves on whole tree growth and competition – an application of the tree growth model ALMIS. Annals of Forest Science, 57: 599-601.

Eschenbach C., 2005. Emergent properties modeled with the functional structural tree growth model ALMIS: computer experiments on resource gain and use. Ecological Modelling, 186: 470-488.

Eschenbach C., Herbst M., Vanselow R., Kappen L., 1996. Transpiration eines Erlenwaldes (*Alnus glutinosa*) und eines Buchenwaldes (*Fagus sylvatica*) an benachbarten Standorten. Verhandlungen der Gesellschaft für Ökologie, 26: 97-103.

Eschenbach C., Kappen L., 1996. Leaf area index determination in an alder forest - a comparison of three methods. Journal of Experimental Botany, 47 (302): 1457-1462.

Eschenbach C., Kappen L., 1999. Leaf water relations of black alder (*Alnus glutinosa* (L.) Gaetrn.) growing at neighboring sites with different water regimes. Trees 14: 28-38.

Eschenbach C., Middelhoff U., 2001. Brauchen wir zwei verschiedene objekt-orientierte Baumwachstumsmodelle für einen Erlenwald? oder struktureller und funktioneller Vergleich des objekt-orientierten Baumwachstumsmodells ALMIS und des Bestandesmodells ARC. In: Rolle und Bedeutung von Modellen für den ökologischen Erkenntnisprozess (Jahrestreffen des GfÖ-Arbeitkreises "Theorie in der Ökologie, Peter Lang Verlag, p. 59-72.

Ewers B.E., Mackay D.S., Gower S.T., Ahl D.E., Burrows S.N., Samanta S.S., 2002. Tree species effects on stand transpiration in northern Wisconsin. Water Resources Research, 38 (7): 81-811.

Fassnacht K.S., Gower S.T., Norman J.M., McMurtire R.E., 1994. A comparison of optical and direct methods for estimating foliage surface area index in forests. Agricultural and Forest Meteorology, 71: 183-207.

Featherstone A.W., 2003. Species profile: Common or black alder (*Alnus glutinosa*). Caledonia Wild! Newsletters, spring 2003. (http://www.treesforlife.org.uk/tfl.alder.html) (acessed: September, 2005).

Federici M., Ulgiati S., Verdeseca D., Basosi R., 2003. Efficiency and sustainability indicators for passenger and commodities transportation systems; the case of Siena, Italy. Ecological Indicators, 3: 155-169.

Fonti P., Garzia-Gonzalez I., 2004. Suitability of chestnut earlywood vessel chronologies for ecological studies. New Phytologist, 163: 77-86.

Ford C.R., Brooks J.R., 2002. Detecting forest stress and decline in response to increasing river flow in southwest Florida. USA Forest Ecology and Management, 160 (1-3): 45-64.

Forest Management Plan for Forestry Unit Dolinsko (Gozdnogospodarski načrt GE Dolinsko), 1959-1968. Zavod za gozdove Slovenije (Slovenia Forest Service) (in Slovene).

Forest Management Plan for Forestry Unit Dolinsko (Gozdnogospodarski načrt GE Dolinsko), 1971-1980. Zavod za gozdove Slovenije (Slovenia Forest Service) (in Slovene).

Forest Management Plan for Forestry Unit Dolinsko (Gozdnogospodarski načrt GE Dolinsko), 1992-2001. Zavod za gozdove Slovenije (Slovenia Forest Service) (in Slovene).

Forest Management Plan for Forestry Unit Dolinsko (Gozdnogospodarski načrt GE Dolinsko), 2002-2011. Zavod za gozdove Slovenije (Slovenia Forest Service) (in Slovene).

Frank E., Hall M., Trigg L., Holmes G., Witten I.H., 2004. Data mining in bioinformatics using Weka. Bioinformatics, 20 (15): 2479–2481.

Franz E.H., Campbell D.E., 2005. Vivantary responsibility and emergy accounting. In: Emergy Synthesis 3: Theory and Application of the Emergy Methodology. Proceedings of the Third Biennial Emergy Conference, January 29 - February 1, 2004. Gainesville, Florida: 229-234.

Funk D.T., 1990. *Alnus glutinosa* (L.) Gaertn., European alder. In: Burns RM, Honkala BH, tech. coords. Silvics of North America. Volume 2, Hardwoods. Washington, DC: USDA Forest Service: 105-115.

Genoni G.P., Meyer E.I., Ulrich A., 2003. Energy flow and elemental concentrations in the Steina River ecosystem (Black Forest, Germany). Aquatic Sciences, 65: 143–157.

Gentili F., Huss-Danell K. 2003. Local and Systemic effects of phosphorus and nitrogen on nodulation and nodule function in *Alnus Incana*. Journal of Experimental Botany, 54: 1-11.

Giannantoni C., 2000. Toward a mathematical formulation of the maximum em-power principle. In: Emergy Synthesis: Theory and Applications of the Emergy Methodology. Proceedings of the First Biennial Emergy Conference, September 2-4, 1999. Gainesville, Florida: 155-170.

Giannantoni C., 2002. The Maximum Empower Principle as the basis for Thermodynamics and Quality. Servizi Grafici Editoriali snc, Padova, Italy, 185 p.

Giannantoni C., 2003. Mathematical formulation of the maximum em-power principle. In: Emergy Synthesis 2: Theory and Applications of the Emergy Methodology. Proceedings of the Second Biennial Emergy Conference, September 20-22, 2001. Gainesville, Florida: 185-202.

Gill C.J., 1975. Ecological significance of adventitious rooting as a response to flooding in woody species, with special reference to *Alnus glutinosa* (L.) Gaertn. Flora, 164 (1): 85-97.

Giordano P.A., Hibbs D.E., 1993. Morphological Response to Competition in Red Alder: The Role of Water. Functional Ecology, 7 (4): 462-468.

Glavač V., 1962. O višinskom rastu johe do dobi od 20 godina (On the height growth rate of black alder up to the age of 20 years). Šumarski list, 88 (11-12): 408-414 (In Croatian, with English summary).

Gochis D.J., Cuenca R.H., 2000. Plant water use and crop curves for hybrid poplars. Journal of Irrigation and Drainage Engineering, 126: 206–214.

Gökkaya K., Hurd T.M., Raynal D.J., 2004. Simbiont nitrogenase, alder growth and soil nitrate response to phosphorus addition in alder (*Alnus incana* ssp. *rugosa*) wetlands of the Adirondack Mountains, New York State, USA. Environmental and Experimental Botany, 55 (1-2): 97-109.

Gonzales-Prieto S.J., Domenach A.M., Beaupied H., Moiroud A., Jocteur-Monrozier L., 1995. Composition of organic-N and 15N-labeling uniformity in alder leaves. Soil Biology and Biochemistry, 21 (7): 925-929.

Goodrich D.C., Scott R., Qi J., Goff B., Unkrich C.L., Moran M.S., Williams D., Schaeffer S., Snyder K., MacNish R., Maddock T., Pool D., Chehbouni A., Cooper D.I., Eichinger W.E., Shuttleworth W.J., Kerri Y., Marsett R., Ni W., 2000. Seasonal estimates of riparian evapotranspiration using remote and in situ measurements. Agricultural and Forest Meteorology, 105: 281–309.

Gordon J.C., Wheeler C.T., 1978. Whole plant studies in photosynthesis and acetylene reduction in *Alnus glutinosa*. New Phytologist, 80 (1): 179-186.

Gower S.T., Norman J.M., 1991. Rapid estimation of leaf area index in conifer and broad-leaf plantations. Ecology, 75 (5): 1896-1900.

Granier A., Biron P., Lemoine D., 2000b. Water balance, transpiration and canopy conductance in two beech stands. Agricultural and Forest Meteorology, 100: 291–308.

Granier A., Bréda N., Biron P., Villette S., 1999. A lumped water balance model to evaluate duration and intensity of drought constraints in forest stands. Ecological Modelling, 116 (2-3): 269-283.

Granier A., Loustau D., Bréda N., 2000a. A generic model of forest canopy conductance dependent on climate, soil water availability and leaf area index. Annals of Forest Science, 57: 755–765.

Grosse W., Schulte A., Fujita H., 1993. Pressurized gas transport in two Japanese alder species in relation to their natural habitats. Ecological Reserch, 8 (2): 151-158.

Grosse W., Frye J., Lattermann S., 1992. Root aeration in wetland trees by pressurized gas-transport. Tree Physiology, 10: 2285–2295.

Grosse W., Schröder P., 1984. Oxygen supply of roots by gas transport in Alder trees. Zeitschshrift fur Naturforschung, 39c: 1186-1188.

Hall R.B., Burgess D., 1990. Evaluation of *Alnus* species and hybrids. Biomass London, 22 (1-4): 21-34.

Hall R.L., Allen S.J., Rosier P.T.W., Hopkins R., 1998. Transpiration from coppiced poplar and willow measured using sap-fow methods. Agricultural and Forest Meteorology, 90: 275-290.

Hau J.L., Bakshi B.R., 2004. Promise and Problems of emergy analysis. Ecological Modelling, 178: 215-225.

Hendrickson O.Q., Burgess D., Perinet P., Tremblay F., Chatatpaul L., 1993. Effects of *Frankia* on field performance of *Alnus* clones and seedlings. Plant and Soil, 150 (2): 295-302.

Hendrickson O.Q., Fogal W.H., Burgess D., 1991. Growth and resistance to herbivory in N_2-fixing alders. Canadian Journal of Botany, 69 (9): 1919-1926.

Herbst M., Eschenbach C., Kappen L., 1999. Water use in neighboring stands of beech and black alder. Annals of Forest Science, 56: 107–120.

Herbst M., Kappen L., 1999. The ratio of transpiration versus evaporation in a reed belt as influenced by weather conditions. Aquatic Botany, 63 (2): 113-125.

Herendeen R.A., 2004: Energy analysis and emergy analysis – a comparison. Ecological Modelling, 178: 227-237.

Hibbs D.E., 1987. The self-thinning rule and red alder management. Forest Ecology and Management, 18: 273-281.

Hibbs D.E., Carlton G.C., 1989. A comparison of diameter- and volume-based stocking guides for red alder. Western Journal of Applied Forestry, 4 (4): 113-115.

Hogg E.H., 1999. Simulation of interannual responses of trembling aspen stands to climatic variation and insect defoliation in western Canada. Ecological Modelling, 114 (2-3): 175-193.

Horaček P., Šlezingerova J., Gandelova L., 2003. Analysis of cambial activity and formation of wood in *Quercus robur* under conditions of a floodplain forest. Journal of Forest Science, 49 (9): 412-418.

Huang S.L., Hsu W.L., 2003. Materials flow analysis and emergy evaluation of Taipei's urban construction. Landscape and Urban Planning, 63: 61–74.

Hurd T.M., Raynal D.J., Schwintzer C.R., 2001. Symbiotic N_2 fixation of *Alnus incana* ssp. *rugosa* in shrub wetlands of the Adirondack Mountains, New York, USA. Oecologia, 126: 94–103.

Hutchings T.R., Moffat A.J., Kemp, R.A., 2001. Effects of rooting and tree growth of selected woodland species on cap integrity on a mineral capped landfill site. Waste Management and Research, 19 (3): 194-200.

Inouye D.W., 2000. The ecological and evolutionary significance of frost in the context of climate change. Ecology Letters, 3: 457-463.

Iremonger S.F., Kelly D.L., 1988. The response of four Irish wetland tree species to raised soil water levels. New Phytologist, 109 (4): 491-497.

Jacks G., Norrström A.C., 2004. Hydrochemistry and hydrology of forest riparian wetlands. Forest Ecology and Management, 196 (2-3): 187-197.

Jensen D.T., Hargreaves G.H., Temesgen B., Allen R.G., 1997. Computation of ET_o under nonideal conditions. Journal of Irrigation and Drainage Engineering, 123 (5): 394-400.

Johansson T., 1999a. Site index curves for common alder and grey alder growing on different types of forest soil in Sweden. Scandinavian Journal of Forest Research, 14 (5): 441-453.

Johansson T., 1999b. Dry matter amounts and increment in 21- to 91-year-old common alder and grey alder and some practical implications. Canadian Journal of Forest Research, 29 (11): 1679-1690.

Johansson T., 2000. Biomass equations for determining fractions of common and grey alders growing on abandoned farmland and some practical implications. Biomass and Bioenergy, 18: 147-159.

Johnson T., 1992. Effects of forest management on soil carbon storage. Water, Air, and Soil Pollution, 64: 83-120.

Jørgensen S.E., 1999. State-of-the-art of ecological modelling with emphasis on development of structural dynamic models. Ecological Modelling, 120 (2-3): 75-96.

Jørgensen S.E., 2002. Integration of Ecosystem Theories: A Pattern. Third edition. Kluwer Academic Publisher, Dordrecht, Boston, London, 420 p.

Jørgensen S.E., DeBernardi R., 1998. The use of structural dynamic models to explain successes and failures of biomanipulation. Hydrobiologia, 379: 147–158.

Jørgensen S.E., Mejer H., Nielsen S.N., 1998. Ecosystems as self-organizing critical systems. Ecological Modelling, 111: 261-268.

Jørgensen S.E., Nielsen S.N., Mejer H., 1995. Emergy, environ, exergy and ecological modelling. Ecological Modelling, 77: 99-109.

Jørgensen S.E., Odum H.T., Brown M.T., 2004. Emergy and exergy stored in genetic information. Ecological Modelling, 178: 11–16.

Kaelke C.M., Dawson J.O., 2003: Seasonal flooding regimes influence survival, nitrogen fixation, and the partitioning of nitrogen and biomass in *Alnus incana* ssp. *rugosa*. Plant and Soil, 254 (1): 167-177.

Kairiukstis L.A., Stravinskiene V.P., 1987. Dendrochronologies for moist forests of the Lithuanian SSR and their application for ecological forecasting. Annales - Academiae Scientiarum Fennicae, Series A III, Geologica- Geographica, 145: 119-135.

Kajfež-Bogataj L., Kurnik B., 2004. Enostavne metode za izračun referenčne evapotranspiracije. Novi izzivi v poljedelstvu: 128-135.

Kalan J., 1988. Pedološke razmere v gozdovih Črnega loga (13. gozdnogospodarsko območje – Murska Sobota) (Pedologic conditions in the forests of Črni Log). Research work. Institute for Forestry and Forest Management, Biotechnical Faculty, Ljubljana, 21 p.

Kangas R.C., 2002. Handbook of Emergy Evaluation, Folio 5: Emergy of Landforms. Center for Environmental Policy, University of Florida. Gainesville, 16p.

Kavvadias V.A., Alifragis D., Tsiontsis A., Brosfas G., Stamatelos G., 2001. Littefall, litter accumulation and litter decomposition rates in four forest ecosystems in northern Greece. Forest Ecology and Management, 144: 113-127.

Kecman M., 1999. Gojitvene lastnosti črne jelše v Polanskem logu (Management properties of black alder in Polanski log). Gozd, 57: 355-367 (in Slovene).

Kecman M., Ferlin F., 2001: Vpliv izbiralnih redčenj na prostorsko razmestitev in prevrščanje dreves v mlajših sestojih črne jelše (The effect of selective thinning in the spatial arrangement and height growth in younger black alder stands). Zbornik gozdarstva in lesarstva, 66: 157-185 (in Slovene).

Keeland B.D., Sharitz R.R., 1997. The effects of water-level fluctuations on weekly tree growth in a southeastern USA swamp. American Journal of Botany, 84 (1): 131-139.

Keitt T.H., 1991. Hierarchical Organization of Energy and Information in a tropical Rain Forest Ecosystem. Masters Thesis, University of Florida, 73 p.

Kergoat L., 1998. A model for hydrological equilibrium of leaf area index on a global scale. Journal of Hydrology, 212-213: 268-286.

Kikuzawa K., 1980. Why do alder leaves fall in summer? Japanese Journal of Ecology, 30: 359-368 (in Japan, with English abstract).

Killingbeck K.T., 1996. Nutrients in senesced leaves: Key to search for potential respiration and resorption proficiency. Ecology, 77 (6): 1716-1727.

Kirdyanov A., Hughes M., Vaganov E., Schweingruber F., Silkin P., 2003. The importance of early summer temperature and date of snow melt for tree growth in the Siberian Subartic. Trees, 17: 61-69.

Knowe S.A., Ahrens G.R., Debell D.S., 1997. Comparison of diameter-distribution-prediction, stand-table-projection, and individual-tree-growth modeling approaches for young red alder plantations. Forest Ecology and Management, 98: 49-60.

Knowe S.A., Hibbs D.E., 1996. Stand structure and dynamics of young red alder as affected by planting density. Forest Ecology and Management, 82: 69-85.

Košir Ž., 1987. Vpliv zadrževalnika Radmožanci na gozdove Črnega loga (Effect of water reservoir Radmožanci on the forests in Črni Log). Research work, elaborate N^{o}244. Inštitut za Gozdno in Lesno Gospodarstvo pri Biotehniški Fakulteti, Ljubljana (in Slovene).

Köstner B., 2001. Evaporation and transpiration from forests in Central Europe - relevance of patch-level studies for spatial scaling. Meteorology and Atmospheric Physics, 76: 69-82.

Kotar M., 1979. Prirastoslovje (Yield Studies). University of Ljubljana, Biotechincal Faculty, 196 p. (in Slovene).

Kotar M., 1986. Prirastoslovje (Yield Studies). 1st reprint. University of Ljubljana, Biotechincal Faculty, 196 p. (in Slovene).

Kotar M., 2003. Gozdarski priročnik (Manual for Forestry). Ljubljana, Biotechnical Faculty, 414 p.

Kotar M., 2005. Zgradba, rast in donos gozda na ekoloških in fizioloških osnovah (Structure, Growth, and Yield of Forest based on Ecology and Physiology). Ljubljana, Zavod za gozdove Slovenije (Slovenian Forestry Service), 500 p. (in Slovene).

Kozlowski T.T., 1982. Water supply and tree growth. Part II. Flooding. Forestry Abstracts, 43: 145–161.

Krstinic A., Gracan J., Kajba D., 2002. Alder genetic resources conservation strategy. In: Noble Hardwoods Network. Report of the 4th meeting, September 4-6, 1999, Gmunden, Sustria and the 5th meeting, 17-19 May, 2001, Blessington, Ireland (Turok J., Erikson G., Russel K., Borelli K.; compilers). IPGRI, Rome, Italy: 44-49.

Kubat M., Bratko I., Michalski R.S., 1997. A review of machine learning methods. In: Michalski R.S., Kubat M., Bratko I. (eds.): Applications of Machine Learning and Knowledge Discovery. Wiley and Sons: 3-70.

Kutsch W.L., Staack A., Wotzel J., Middelhof U., Kappen L., 2001. Field measurements of root respiration and total soil respiration in an alder forest. New Phytologist, 150: 157-168.

Kuzmin P.P., Vershinin A.P., 1974. Determination of evaporation in case of the absence or inadequacy of data. Proceedings of the Madrid Symposium. Studies and reports in hydrology. UNESCO-WMO-IASH, 16: 217-226.

Laganis J., Debeljak M., 2006. Sensitivity analysis of the emergy flows at the solar salt production process in Slovenia. Ecological Modelling, 194 (1-3): 287-295.

Langley P., Sanchez J., Todorovski L., Dzeroski S., 2002. Inducing process models from continuous data. Proceedings of the Nineteenth International Conference on Machine Learning, 8 p.

Le Maitre D.C., Versfeld D.B., 1997. Forest evaporation models: relationships between stand growth and evaporation. Journal of Hydrology, 193 (1): 240-257.

Lebaube S., Le Goff N., Ottorini J.M., Granier A., 2000. Carbon balance and tree growth in a *Fagus sylvatica* stand. Annals of Forest Science, 57: 49–61.

Lechowicz M.J., 1984. Why do temperate deciduous trees leaf out at different times? Adaptation and ecology of forest communities. The American Naturalist, 124: 821-842.

Leofroy E., Rydberg T., 2003. Emergy evaluation of three cropping systems in southwestern Australia. Ecological Modelling, 3197: 1-17.

Levanič T., 1993: Effects of hidromelioration on growth and increment characteristics of black alder (*Alnus glutinosa* (L.) Gaertn.), ash (*Fraxinus angustifolia* Vahl.) and oak (*Quercus robur* L.) in Prekmurje. Master of science thesis, University of Ljubljana (in Slovene).

Levanič T., Kotar M., 1996. The effect of hydroameliorations on the forest conditions at Črni log. In: Drainage and Environment, 6th ICID Drainage Workshop, April 22-24, 1996. Ljubljana, Slovenia.

Levanič T., 2005. Osnove dendrokronologije, študijsko gradivo za podiplomski študij, delovna verzija (Basics of dendrochronology for post-degree students, working version; in Slovene). 76 p.

Lhomme J.P., 1997. A theoretical basis for the Priestley-Taylor coefficient. Boundary-Layer Meteorology, 82 (2): 179-191.

Liepe K., 1990. Growth and root development of 30-year-old black alder (*Alnus-glutinosa* (L.) Gaertner) of a provenance trial. Allgemeine Forst- und Jagdzeitung, 161 (8): 149-154 (in German).

Månsson B.Å., McGlade J.M., 1993. Ecology, thermodynamics and H.T. Odum's conjectures. Oecologia, 93: 582-596.

Martens S.N., Ustin S.L., Rosseau R.A., 1993. Estimation of tree canopy leaf area index by gap fraction analysis. Forest Ecology and Management, 61: 91-108.

Martin J.F., 2002. Emergy valuation of diversions of river water to marshes in the Mississippi River Delta. Ecological Engineering, 18: 265-286.

McCray-Batzli J., Dawson J.O., 1999. Development of flood-induced lenticels in red alder nodules prior to the restoration of nitrogenase activity. Canadian Journal of Botany, 77(9): 1373–1377.

McVean D.N., 1953. Biological flora of the British Isles: *Alnus glutinosa* (L.) Moench. Journal of Ecology, 41 (2): 447-466.

McVean D.N., 1956a. Ecology of *Alnus glutinosa* (L.) Moench: IV. Root system. The Journal of Ecology, 44 (1): 219-225.

McVean D.N., 1956b. Ecology of *Alnus glutinosa* (L.) Moench: V. Notes on some British Isles populations. The Journal of Ecology, 44 (2): 321-330.

Middelhof U., Breckling, 2005. From single fine roots to black alder forest ecosystem: How system behavior emerges from single component activities. Ecological Modelling, 186 (4): 447-469.

Middelhoff U., 2000. Simulationsgestützte Analyse der raum-zeitlichen Verteilung der Biomasse in einem Erlenwald unter besonderer Beachtung der Feinwurzeldynamik. Dissertation, University of Kiel, 140 p.

Mlinšek D., 1961. Rast in ospodarska vrednost črne jelše (Growth and economical importance of black alder). Murska Sobota, Izvršni svet za kmetijstvo in gozdarstvo, 32 p. (in Slovene).

Moffat A.J., 2000. Effect of inoculation with *Frankia* on the growth and nutrition of alder species and interplanted Japanese larch on restored mineral workings. Forestry, 73 (3): 215-223.

Moiroud M., Faure-Raynaud M., Simonet P., 1984. Influence de basses temperatures sur la croissance et la survie de souches pures de *Frankia* isolees de nodules d'Aulnes. Influence of low temperatures on the growth and viability of pure strains of *Frankia* isolated from *Alder* nodules. Plant and Soil, 78: 91-97.

Monzón A., Azcón R., 2001. Growth responses and nitrogen and phosphorus use efficiency of three *Alnus* species as affected by arbuscular-mycorrhizal colonization. Plant Growth Regulation, 35 (1): 97-104.

Moore G.W., Bond B.J., Jones J.A., Philips N., Meinzer F.C., 2004. Structural and compositional controls of transpiration in 40- and 450-year-old riparian forests in western Oregon, USA. Tree Physiology, 24: 481-491.

Myrold D.D., Huss-Danell K., 2003. Alder and lupine enhance nitrogen cycling in a degraded forest soil in Northern Sweden. Plant and Soil, 254: 47–56.

Neave I.A., Dawson J.O., Delucia E.H., 1989. Autumnal photosynthesis is extended in nitrogen-fixing European black alder compared with white basswood: possible adaptive significance. Canadian Journal of Forest Research, 19 (1): 12-17.

Nemesszeghy L., 1986. Črna jelša v Prekmurju (Black alder in Prekmurje). Pomurska založba, Murska Sobota, 88 p. (in Slovene).

Odum H.T., 1983. Maximum power and efficiency: a rebuttal. Ecological Modelling, 20: 71-82.

Odum H.T., 1988. Self-organization, transformity and information. Science, 242: 1132-1139.

Odum H.T., 1995a. Energy system concepts and self-organization: a rebuttal. Oecologia, 104: 518-522.

Odum H.T., 1995b. Nature’s pulsing paradigm. Estuaries, 18 (4): 547-555.

Odum H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. John Willey and Sons, New York, 370 p.

Odum H.T., 1998. Emergy evaluation. International Energy Analysis Workshop, Porto Venere, Italy.

Odum H.T., 2000a. An energy hierarchy law for biogeochemical cycles. In: Emergy Synthesis: Theory and Applications of the Emergy Methodology. Proceedings of the First Biennial Emergy Conference, September 2-4, 1999. Gainesville, Florida: 235-248.

Odum H.T., 2000b. Emergy Accounting. Environmental Engineering Sciences, University of Florida, Gainesville, USA.

Odum H.T., 2000c. Handbook of Emergy Evaluation, Folio 2: Emergy of Global Processes. Center for Environmental Policy, University of Florida, Gainesville, 30p.

Odum H.T., 2002. Explanations of ecological relationships with energy systems concepts. Ecological Modelling, 158: 201-211.

Odum H.T., 2003. Energy hierarchy and transformity in the universe. In: Emergy Synthesis 2: Theory and Applications of the Emergy Methodology. Proceedings of the Second Biennial Emergy Conference, September 20-22, 2001. Gainesville, Florida: 1-14.

Odum H.T., Brown M.T., Brandt-Williams S., 2000. Handbook of Emergy Evaluation, Folio 1: Introduction and Global Budget. Center for Environmental Policy, University of Florida, Gainesville, 16p.

Odum H.T., Collins D., 2003. Transformities from ecosystem energy webs with eigenvalue method. In: Emergy Synthesis: Theory and Applications of the Emergy Methodology. Proceedings of the Second Biennial Emergy Conference, September 20-22, 2001. Gainesville, Florida: 203-220.

Odum H.T., Odum E.C., 1999. Modeling for All Scales. An Introduction to Systems Simulation. Academic Press, San Diego, California, 491 p.

Odum H.T., Odum E.C., 2001a. The prosperous way down. University Press of Colorado, 326 p.

Odum H.T., Odum E.C., 2001b. The prosperous way down. In: Proceedings of the Second International Workshop, Advances in Energy Studies. May 23-27, 2000. Porto Venere, Italy, 361-366.

Odum H.T., Odum E.C., 2006. The prosperous way down. Energy, 31: 21–32.

Odum H.T., Peterson N., 1996. Simulation and evaluation with energy systems blocks. Ecological Modelling, 93: 155-173.

Ogrin D., 1989. Dendrokronologija in možnosti uporabe njene metode v Sloveniji (Dendrochronology and possibilities for its application in Slovenia). Geografski vestnik, 61: 133-140 (in Slovene).

Ogrin D., 2000/2001. Vpliv suše na debelinski prirastek dreves (Effect of drought on the radial increment of trees). Ujma 14/15: 47-57.

Oliveira G., Correia O., Martinsloucao M., Catarino F.M., 1994. Phenological and growth patterns of the Mediterranean oak *Quercus suber* L. Trees - Structure and Function, 9 (1): 41-46.

Pan Y., Raynal D.J., 1995. Decomposing tree annual volume increments and constructing a system dynamic model of tree growth. Ecological Modelling, 82: 299-312.

Parker J., 1968. Drought resistance of roots of white ash, sugar maple, and red oak. US Forest Research Paper N°95. Northeastern Forest Experiment Station, Upper Darby, PA, 11 p.

Patten B.C., 1993. Toward a more holistic ecology, and science: the contribution of H.T. Odum. Oecologia, 93: 597-602.

Patten B.C., 1995. Network integration of ecological extremal principles: Exergy, emergy, power, ascendency, and indirect effects. Ecological Modelling, 79 (1-3): 75-84.

Pečkov A., Todorovski L., Džeroski S., 2006. Proper versus ad hoc MDL principle for Polynomial regression. In: Conference on Data Mining and Data Warehouses (SiKDD 2006), October 9, 2006. Ljubljana, Slovenia, 4 p.

Pereira J.T.V., Nebra S.A., 2000. Transformities and exergetic cost – a discussion. Emergy Synthesis: Theory and applications of the emergy methodology. Proceedings of the First Biennial Emergy Conference, September 2-4, 1999. Gainesville, Florida: 71-80.

Pezeshki S.R., Hinckley T.M., 1988. Water relations of *Alnus rubra* and *Populus trichocarpa*: responses to field drought. Canadian Journal od Forest Research, 18: 1159-1166.

Pizelle G., 1984. Seasonal-variations of the sexual reproductive growth and nitrogenase activity (C_2H_2) in mature *Alnus-glutinosa*. Plant and Soil, 78 (1-2): 181-188.

Planchais I., Pontailler J.Y., 1999. Validity of leaf areas and angles estimated in a beech forest from analysis of gap frequencies, using hemispherical photographs and a plant canopy analyzer. Annals of Forest Sciences, 56: 1-10.

Pregent G., Camire C., 1985. Mineral nutrition, dinitrogen fixation, and growth of *Alnus crispa* and *Alnus glutinosa*. Canadian Journal of Forest Research, 15: 855-861.

Pretzell D., Knor E.M., Reif A.,1997. Degradation of alder swamp forest in the upper Rhine Valley (Degradation von Erlenbruchwaldern in der Oberrheinebene.). Verhandlungen-Gesellschaft-fur-Okologie, 27: 435-440 (in German, with English abstract).

Pritsch K., 1997. Morphological and anatomical characterization of black alder mycorrhizas. Mycorrhiza, 7: 201-216.

Pritsch K., Munch J.C., Buscot F., 1997. Morphological and anatomical characterisation of black alder *Alnus glutinosa* (L.) Gaertn. ectomycorrhizas. Mycorrhiza, 7 (4): 201-216.

Quispel A., Tak T., 1978. Studies on the growth of the endophyte of *Alnus glutinosa* (L.) Vill. In nutrient solutions. New Phytologist, 81 (3): 587-600.

Raguei M., Bargigli S., Ulgiati S., 2005. Emergy "Yield" Ratio – problems and misapplications. In: Emergy Synthesis 3: Theory and applications of the emergy methodology. Proceedings of the Third Biennial Emergy Conference, January 29-31, 2004. Gainesville, Florida: 159-164.

Roberts J., 1983. Forest transpiration: A conservative hydrological process? Journal of Hydrology, 66 (1-4): 133-141.

Roberts J.M., Gowing D.J., Herbst M., Callaghan N., Rosier P.T.W., 2001. The influence of woodlands on recharge in the Pang catchment. NERC LOCAR Third Science Meeting Project Outcome Summary, 2 p.

Robertson S.M.C., Hornung M., Kennedy V.H., 2000. Water chemistry of throughfall and soil water under four tree species at Gisburn, northwest England, before and after felling. Forest Ecology and Management, 129: 101-117.

Robin L., Hall R.L., Allen S.J., Rosier P.T.W., Hopkins R., 1998. Transpiration from coppiced poplar and willow measured using sap-flow methods. Agricultural and Forest Meteorology, 90: 275-290.

Rockström J., Gordon L., Folke C., Falkenmark M., Engwall M., 1999. Linkages Among Water Vapor Flows, Food Production, and Terrestrial Ecosystem Services. Ecology and Society, 3 (2): 5.

Rodríguez-Barrueco C., Miguel C., Subramaniam P., 1984. Seasonal fluctuations of the mineral concentration of alder (*Alnus glutinosa* (L.) Gaertn.) from the field. Plant and Soil, 78: 201-208.

Rötzer T., Grote R., Pretzsch H., 2004. The timing of bud burst and its effect on tree growth. International Journal of Biometeorology, 48: 109-118.

Rusch H., Rennenberg H., 1998. Black alder (*Alnus glutinosa* (L.) Gaertn.) trees mediate methane and nitrous oxide emission from the soil to the atmosphere. Plant and Soil, 201 (1): 1-7.

Samson R., 2001. An experimental and modelling approach to the actual evapotranspiration in a mixed forest ecosystem (Experimental forest Aelmoeseneie at Gontrode). PhD thesis, University of Gent, 294 p.

Sayed W.F., 2003. Effects of land irrigation with partially-treated wastewater on *Frankia* survival and infectivity. Plant and Soil, 254: 19–25.

Scatena F.N., Doherty S.J., Odum H.T., Kharecha P., 2002. An Emergy Evaluation of Puerto Rico and the Luquillo Experimental Forest. General Technical Report IITF-GTR-9. U.S. Departure of Agriculture, Forest Service, International Institute of Tropical Forestry. Rio Piedras, 79 p.

Scheifinger H., Menzel A., Koch E., Peter C., 2003. Trends of spring time frost events and phonological dated in Central Europe. Theoretical and Applied Climatology, 74: 41-51.

Schmitt U., Jalkanen R., Eckstein D., 2004. Cambium dynamics of *Pinus sylvestris* and *Betula* spp. in the northern Borela forest in Finnland. Silva Fennica, 38 (2): 167-178.

Schrader J.A., Gardner S.J., Graves W.R., 2004. Resistance to water stress of *Alnus maritima*: Intraspecific variation and comparisons to other alders. Environmental and Experimental Botany, 53: 281-198.

Schröder P., 1989. Characterization of a thermo-osmotic gas transport mechanism in *Alnus glutinosa* (L.) Gaertn. Trees - Structure and Function, 3 (1): 38-44.

Seiler J.R., 1985. Morphological and Physiological changes in black alder induced by water stress. Plant, Cell and Environment, 8: 219-222.

Seiler J.R., McCormick L.H., 1982. Effect of forest acidity and phosphorus on the growth and nodule development of black alder. Canadian Journal of Forest Research, 12: 576-581.

Shiau S.Y., Davar K.S., 1973. Modified Penman method for potential evapotranspiration from forest regions. Journal of Hydrology, 18 (3-4): 349-365.

Shipton W.A., Burggraaf A.J.P., 1982. *Frankia* growth and activity as influenced by water potential. Plant and Soil, 69 (2): 293-297.

Silvicultural Chronicle, 1971-1992. Forest Management Region Murska Sobota, Forest Management Unit Dolinsko.

Singh K.A., Thompson F.B., 1995. Effect of lopping on water potential, transpiration, regrowth, C-14 photosynthate distribution and biomass production in *Alnus-glutinosa*. Tree Physiology, 15 (3): 197-202.

Smolej I., 1995. Hydrological conditions on permanent research plots. In: Oak Decline in Slovenia. Final report. Ljubljana, Wien, Forestry Institute, Institut für Waldökologie, 213 p.

Snyder R.L., Spano D., Cesaraccio C., Duce P., 1999. Determining degree-day thresholds from field observations. International Journal of Biometeorology, 42: 177-182.

Spano D., Cesaraccio C., Duce P., Snyder R.L., 1999. Phenological stages of natural species and their use as climate indicators. International Journal of Biometeorology, 42: 124-133.

Šraj M., 2003. Modelling and Measuring of intercepted precipitation. Doctoral thesis, University of Ljubljana, 236 p.

Stahle D.W., Mushove P.T., Cleaveland M.K., Roig F., Haynes G.A., 1999. Management implications of annual growth rings in *Pterocarpus angolensis* from Zimbabwe. Forest Ecology and Management, 124 (2-3): 217-229.

Stone E.L., Kalisz P.J., 1991. On the maximum extent of tree roots. Forest Ecology and Management, 46: 59-102.

Stravinskene V.P., 1983. Dynamics of early and late wood in the annual rings of trees and its change due to forest drainage. Soviet Journal of Ecology, 14 (6): 324-328.

SURS, Statistical Office of the Republic of Slovenia (Statistični urad Republike Slovenije). Data available on the webpage http://www.stat.si/index.asp (acessed: 2004, 2005, 2006).

Sušnik A., 2003. Dinamika primanjkljaja vode za kmetijske rastline včeraj, danes in jutri (Dynamics of water deficiency for agricultural plants). 14. Mišičev Vodarski Dan: Proceedings (http://www.arso.gov.si/o_agenciji/knji~znica/publikacije/Dinamika_primanjkljaja_vode.pdf), 8 p. (in Slovene),.

Sušnik A., Matajc I., 2004. Novi pristopi pri vrednoteju oskrbe rastlin z vodo (New Concepts in the Management of Crop Water Supply). In: New Challenges in Field Crop Production, Proceedings of a Symposium, December 13-14, 2004, Čatež ob Savi, Slovenia (In Slovene, with English summary).

Taulavuori K., 2006. A simple method to visualize the mechanism why *Alnus glutinosa* remains green during autumn colouration of *Sorbus aucuparia*. Trees, 20: 28–33.

Teissier du Cros E., Jung G., Bariteau M., 1984. Alder-Frankia interaction and alder-poplar association for biomass production. Plant and Soil, 78: 235-243.

Thibaut A., Claessens H., Rondeux J., 2004. Site index curves for *Alnus glutinosa* (L.) Gaertn. in southern Belgium: Effect of site on curve shape. Forestry, 77 (2): 157-171.

Tilley D.R., 1999. Emergy Basis of Forest Systems. Dissertation, University of Florida, USA, 296 p.

Tilley D.R., 2003. Industrial ecology and ecological engineering; opportunities for symbiosis. Journal of Industrial Ecology, 2: 13-32.

Tilley D.R., Brown M.T., 2006. Dynamic emergy accounting for assessing the environmental benefits of subtropical wetland stormwater management systems. Ecological Modelling, 192: 327–361.

Tilley D.R., Swank W.T., 2003. Emergy-based environmental systems assessment of multi-purpose temperate mixed-forest watershed of the southern Appalachian Mountains, USA. Journal of Environmental Management, 69: 213-227.

Todorovski L., Ljubič P., Džeroski S., 2004. Inducing polynomial equations for regression. Lecture Notes in Artificial Intelligence (Subseries of Lecture Notes in Computer Science), 3201: 441-452.

Tognetti R., Borghetti M., 1994. Formation and seasonal occurrence of xylem embolism in *Alnus cordata*. Tree Physiology, 14: 241-250.

Torellli N., 2001. Črna jelša – lesna zgradba in obdelavnostne lastnosti (Black alder – structure of wood and handling properties). Les, 53: 424-429 (in Slovene).

Ulgiati S., 2000. Emergy, emergy and embodied exergy: diverging or converging approaches? In: Emergy Synthesis: Theory and Applications of the Emergy Methodology. Proceedings of the First Biennial Emergy Conference, September 2-4, 1999. Gainesville, Florida: 15-32.

Ulgiati S., Bargigli S., Raguei M., 2005. Dotting the I's and crossing the T's of emergy synthesis: material flows, information and memory aspects, and performance indicators. In: Emergy Synthesis 3: Theory and applications of the emergy methodology. Proceedings of the Third Biennial Emergy Conference, January 29-31, 2004. Gainesville, Florida: 199-214.

Ulgiati S., Brown M.T., 2002. Quantifying the environmental support for dilution and abatement of process emissions. The case of electricity production. Journal of Cleaner Production, 10: 335–348.

Ulgiati S., Brown M.T., Bastianoni S., Marchettini N., 1995. Emergy based indices and ratios to evacuate sustainable use of resources. Ecological Engineering, 5: 519-531.

Uliassi D.D., Ruess R.W., 2002. Limitations to symbiotic nitrogen fixation in primary succession on the Tanana River floodplain. Ecology, 83: 88-103.

UN-ECE, 2000. International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests. Manual on Methods and Criteria for Harmonized Sampling, Assessment, Monitoring and Analysis of the Effects of Air Pollution on Forests. Part IV: Sampling and analysis of needles and leaves (http://www.icp-forests.org/Manual.htm). Acessed: January, 2004.

UN-ECE, 2004a. Sampling and Analysis of Litterfall. In: Manual on Methods and Criteria for Harmonized Sampling, Assessment, Monitoring and Analysis of the Effects of Air Pollution on Forests. International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests, 18 p. (http://www.icp-forests.org/Manual.htm). Acessed: January, 2004.

UN-ECE, 2004b. International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests. Manual on Methods and Criteria for Harmonized Sampling, Assessment, Monitoring and Analysis of the Effects of Air Pollution on Forests. Part II: Visual assessment of crown conditions and Submanual on visual assessment of crown conditions on intensive monitoring plots, 38 p. (http://www.icp-forests.org/Manual.htm). Acessed: January, 2004.

UN-ECE, 2004c. International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests. Manual on Methods and Criteria for Harmonized Sampling, Assessment, Monitoring and Analysis of the Effects of Air Pollution on Forests. Part V: Estimation of Growth and Yield, 40 p. (http://www.icp-forests.org/Manual.htm). Acessed: January, 2004.

Urbančič M., Simončič P., Smolej I., 2000. Pedunculate oak stands in the lowland regions of Slovenia – soil water conditions. Časnik za šumske pokuse, 27: 215-228.

Uri V., Lohmus K., Tullus H., 2003a. Annual net nitrogen mineralization in a grey alder (*Alnus incana* (L.) Moench) plantation on abandoned agricultural land. Forest Ecology and Management, 184: 167–176.

Uri V., Tullus H., Lõhmus K., 2002. Biomass production, and nutrient accumulation in short-rotation red alder plantaton on abandoned agricultural land. Forest Ecology and Management, 161: 169-179.

Uri V., Tullus H., Lõhmus K., 2003b. Nutrient Allocation, Accumulation and Above-Ground Biomass in Grey Alder and Hybrid Alder Plantations. Silva Fennica, 37 (3): 301–311.

Valentini R., Matteucci G., Dolman A.J., Schulze E.D., Rebmann C., Moors E.J., Granier A., Gross P., Jensen N. O., Pilegaard K., Lindroth A., Grelle A., Bernhofer C., Gruünwald T., Aubinet M., Ceulemans R., Kowalski A.S., Vesala T., Rannik Ü., Berbigier P., Loustau D., Guðmundsson J., Thorgeirsson H., Ibrom A., Morgenstern K., Clement R., Moncrieff J., Montagnani L., Minerbi S., Jarvis P. G., 2000. Respiration as the main determinant of carbon balance in European forests. Nature, 404: 861-865.

Van Praag H.J., Sougnez-Remy S., Weissen F., Carletti G., 1988. Root turnover in a beech and a spruce stand of the Belgian Ardennes. Plant and Soil, 105: 87–103.

Vares A., Lohmus K., Truu M., Truu J., Tullus H., Kanal A., 2004. Productivity of black alder (*Alnus glutinosa* (L.) Gaertn.) plantations on reclaimed oil-shale mining detritus and mineral soils in relation to rhizosphere conditions. Goryuchiye Slantsy (Tallinn, l984), 21 (1): 43-58.

Verstraeten W.W., Muys B., Feyen J., Veroustraete F., Minnaert M., Meiresonne L., De Schrijver A., 2000. Comparative analysis of the actual evapotranspiration of Flemish forest and cropland, using the soil water balance model WAVE. Hydrology and Earth System Sciences, 9: 225–241.

Vieira R., Samões A., Domingos T., 2005. An exploration of the use of emergy in sustainability evaluation. In: Emergy Synthesis 3: Theory and applications of the emergy methodology. Proceedings of the Third Biennial Emergy Conference, January 29-31, 2004. Gainesville, Florida: 373-384.

Vilhar U., 2006. Vodna bilanca dinarskega jelovo-bukovega gozda v kočevskem rogu (Water Balance of a Dinaric Silver Fir-Beech Forest in Kočevski Rog). Dissertation, University of Ljubljana, 248 p. (in Slovene).

Vogel C.S., Dawson J.O., 1991. Nitrate reductase activity, nitrogenase activity and photosynthesis of black alder exposed to chilling temperatures. Physiologia Plantarum, 82 (4): 551–558.

Vogel C.S., Curtis P.S., Thomas R.B., 1997. Growth and nitrogen accretion of dinitrogen-fixing *Alnus glutinosa* under elevated CO_2. Plant Ecology, 130 (1): 63-70.

Vogel C.S., Dawson J.O., 1993. Changes in tissue nitrogen and phosphorus and foliar free amino acids in autumn olive, black locust, American sycamore, and honey locust during autumn. Canadian Journal of Forest Research, 23 (4): 665-672.

Wagenführ R., 1996. Holzatlas, 4th edition. Fachbuchverlag, Leipzig, 688 p.

Wall L.G., Hellsten A., Huss-Danell K., 2000. Nitrogen, phosphorus, and the ratio between them affect nodulation in *Alnus incana* and *Trifolium pretense*. Symbiosis, 29 (2): 91-105.

Waring R.H., 1987. Characteristics of trees predisposed to die. Bioscience, 37: 569-574.

Welles J.M., Norman J.M., 1991: Instrument for indirect measurement of canopy architecture. Agronomy Journal, 83: 818-825.

Wheeler C.T., 1971. The causation of diurnal changes in nitrogen fixation in the nodules of *Alnus glutinosa*. New Phytologist, 70 (3): 487-495.

White M.A., Running S.W., Thornton P.E., 1999. The impact of growing season length variability on carbon assimilation and evapotranspiration over 88 years in the eastern US deciduous forest. International Journal of Biometeorology, 42:139–145.

Whitehead D., 1998. Regulation of stomatal conductance and transpiration in forest canopies. Tree Physiology, 18: 633-644.

Wieβner A., Kuschk P., Stottmeister U., 2002. Oxygen Release by Roots of *Typha latifolia* and *Juncus effusus* in Laboratory Hydroponic Systems. Acta Biotechnologica, 22 (1-2): 209-216.

Wilson K.B., Hanson P.J., Baldocchi D.D., 2000. Factors controlling evaporation and energy partitioning beneath a deciduous forest over an annual cycle. Agricultural and Forest Meteorology, 102: 83–103.

Wilson K.B., Hanson P.J., Mulholland P.J., Baldocchi D.D., Wullschleger S.D., 2001. A comparison of methods for determining forest evapotranspiration and its components: Sap-flow, soil water budget, eddy covariance and catchment water balance. Agricultural and Forest Meteorology, 106 (2): 153-168.

Woodwell J.C., 1998. A simulation model to illustrate feedbacks among resource consumption, production, and factors of production in ecological-economic systems. Ecological Modelling, 112: 227-247.

Wraber M., 1951. Gozdna vegetacijska slika in gozdnogojitveni problemi Prekmurja (Illustration of forest vegetation and problems of forest management in Prekmurje). Geografski vestnik (Bulletin of the Association of the Geographical Societies of Slovenia), 23: 179-230.

Yang H., Li Y., Shen J., Hu S., 2003. Evaluating waste treatment, recycle and reuse in industrial system: application of the emergy approach. Ecological Modelling, 160: 13-21.

Yang Y., Watanabe M., Li F., Zhang J., Zhang W., Zhai J., 2006. Factors affecting forest growth and possible effects of climate change in the Taihang Mountains, northern China. Forestry, 79 (1): 135-147.

Zhang H., Morison J.I.L., Simmonds L.P., 1999. Transpiration and water relations of poplar trees growing close to the water table. Tree Physiology, 19: 563-573.

Zhang H., Simmonds L.P., Morison J.I.L., Payne D., 1997. Estimation of transpiration by single trees: Comparison of sap flow measurements with a combination equation. Agricultural and Forest Meteorology, 87 (2-3): 155-169.

Zhang L.J., Bi H.Q., Cheng P.F., Davis C.J., 2004. Modelling spatial variation in tree diameter-height relationship. Forest Ecology and Management 189. Water Resources Research, 40 (2): W025021.

Zhang S.H., Romane F.,1991. Diameter growth variation in *Quercus ilex* L. in relation to the climate (Variations de la croissance radiale de *Quercus ilex* L. en fonction du climat). Annales des Sciences Forestieres, 48 (2): 225-234.

Zhu Z.X., Arp P.A., Meng F.R., Bourque C.P.A., Foster N.W., 2003. A Forest Nutrient Cycling and Biomass Model (ForNBM) based on year-round, monthly weather conditions Part II: Calibration, verification, and application. Ecological Modelling, 170: 13–27.

Zmazek B., Todorovski L., Džeroski S., Vaupotič J., Kobal I., 2003. Application of decision trees to the analysis of soil radon data for earthquake prediction. Applied Radiation and Isotopes, 58: 697–706.

Zupanc V., Pintar M., 2001. Melioracije in urejanje kmetijskih zemljišč; Gradivo za vaje (Meliorations and Management of agricultural land; Material for practical work). University of Ljubljana, Biotechnical Faculty, Ljubljana, 66 p.

APPENDIX A: Annual increments and growth of individual trees

Radial growth

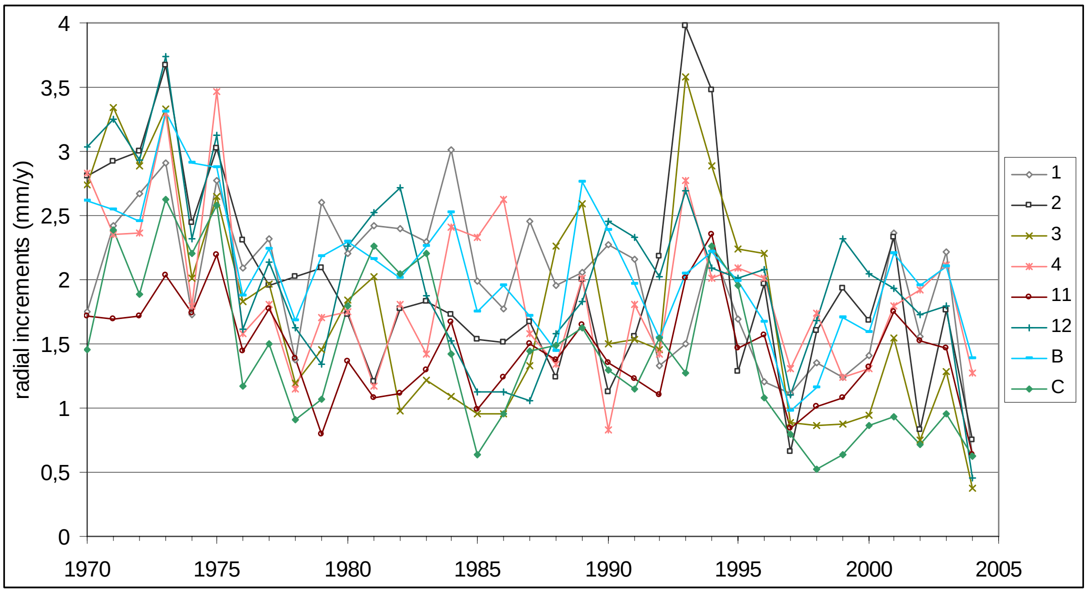


Figure A1 *Radial increments of thee eight trees in the last 35 years (mm).*

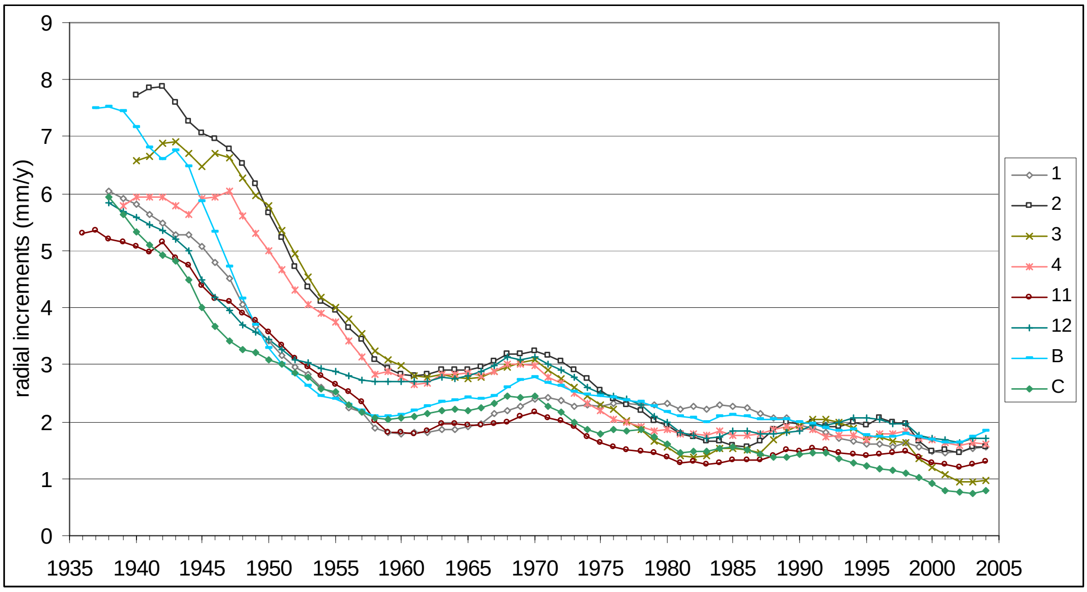
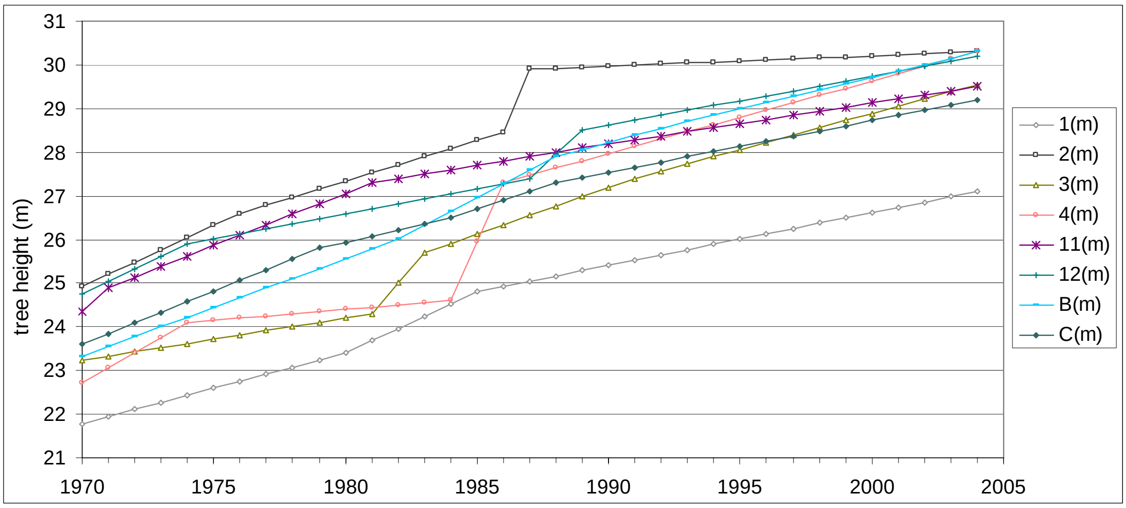


Figure A2 *Five-days moving averages of radial increments at the level 1 of the trees under study.*

Vertical growth

A



B

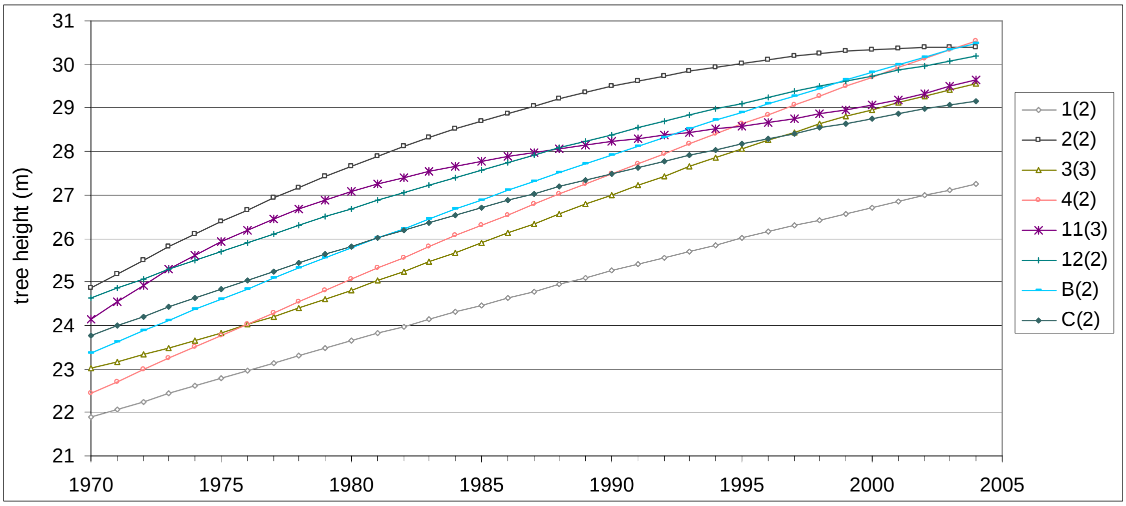
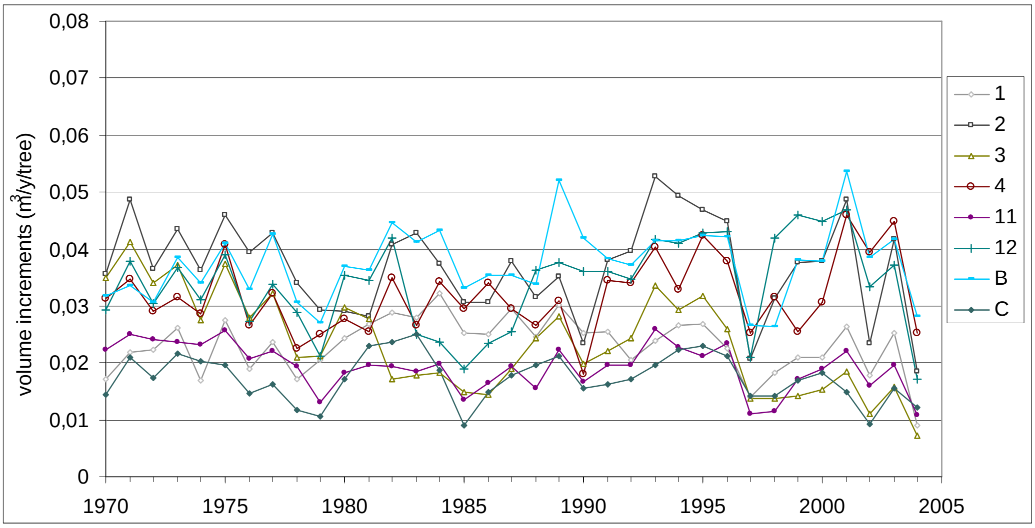


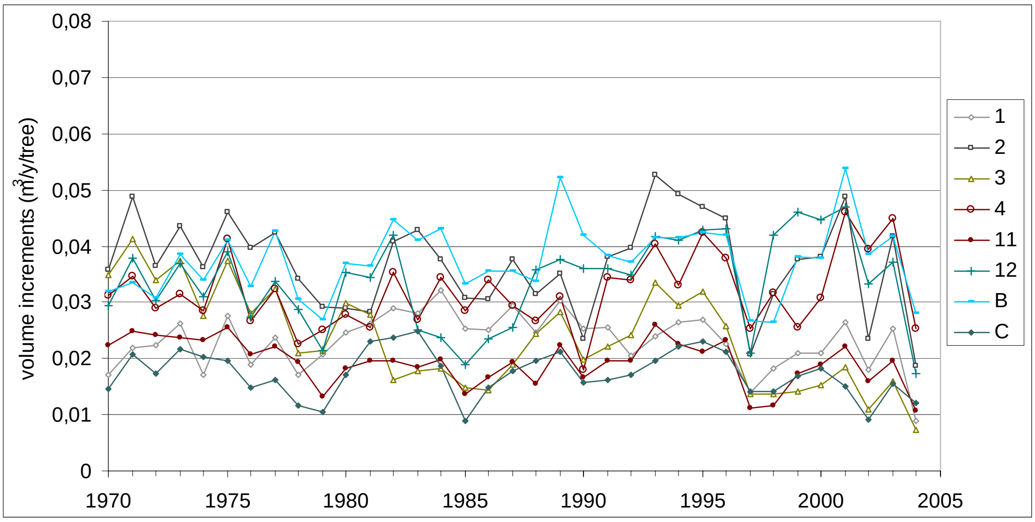
Figure A3 *Height growth: A: Growth curves for "measured" height increments; the data for 35 years. B: "Modeled" growth curves of individual trees. Data for 35 years.*
((m): measured values; (2): the polynomial regression equation of the second order and (3) of the third order).

Volume increments

A



B



C

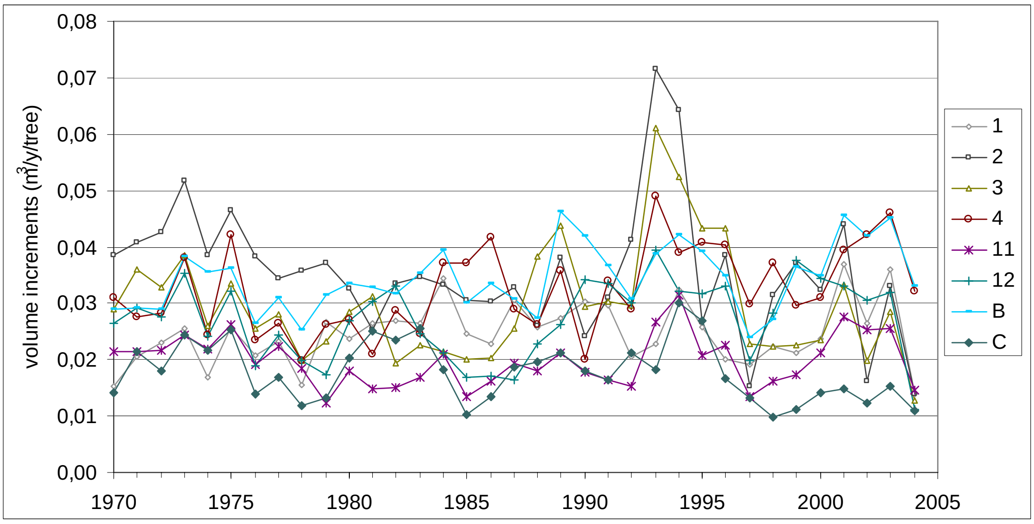
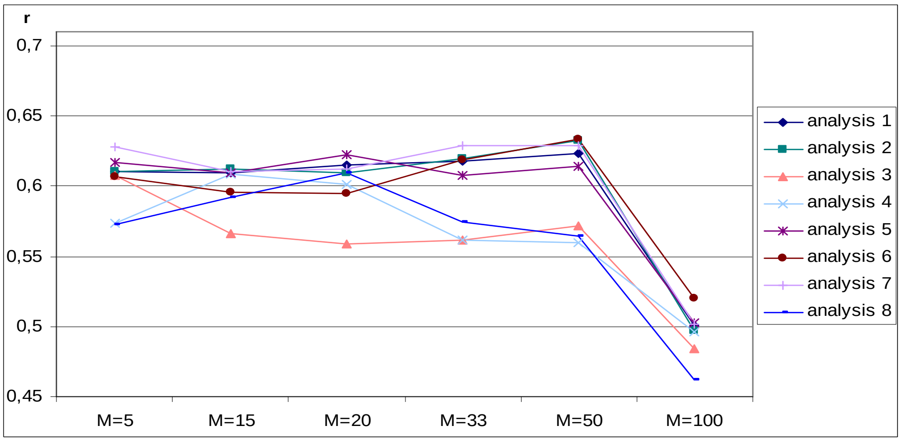


Figure A4 *Volume increments (m^3) of the individual trees (1 to C), calculated with (A) measured diameters and measured heights; (B) measured diameters and modeled heights, and (C) trunk biomass increments calculated using Puhek's equation, measured diameters and modeled heights.*

APPENDIX B: Model and regression trees: model selection



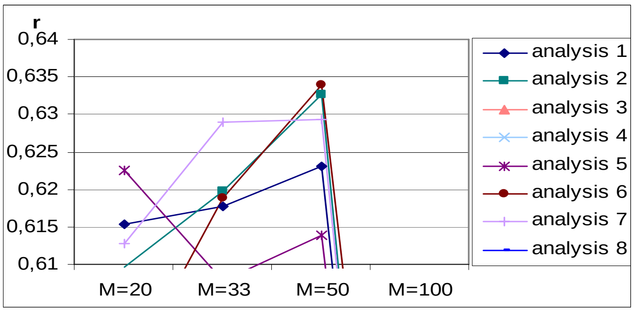
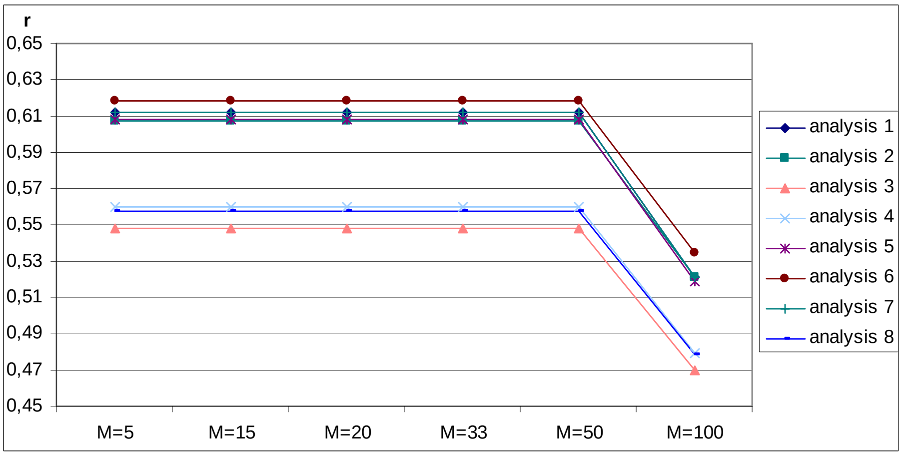


Figure B1 *Overview of the correlation coefficients as indicators of the quality of the models (model trees) generated with different sets of attributes (analyses 1-8) and at different degrees of pruning (M) (10x cross validation). The lower picture enlarges the part with the largest coefficients.*



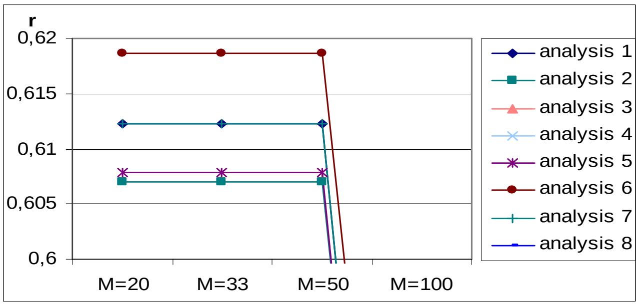
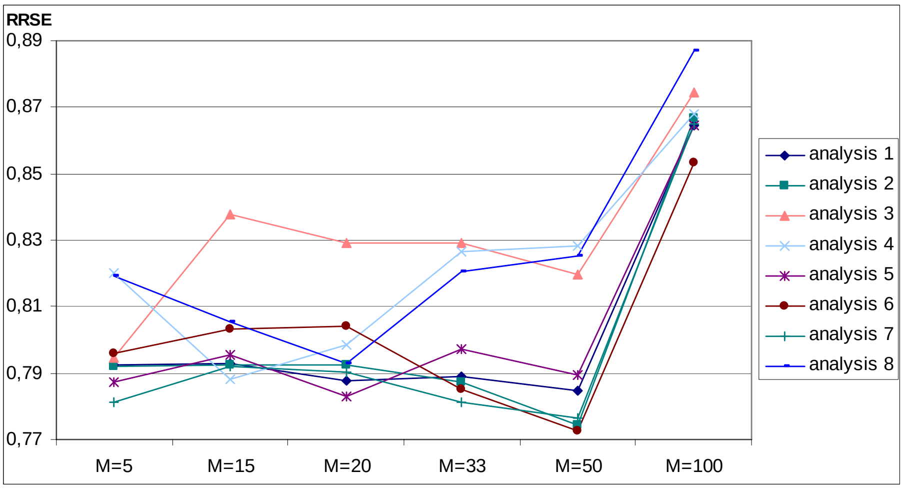


Figure B2 *Overview of regression correlation coefficients as indicators of the quality of models (model trees) generated with different sets of attributes (analyses 1-8) and different degrees of pruning (M) (10x cross validation).*



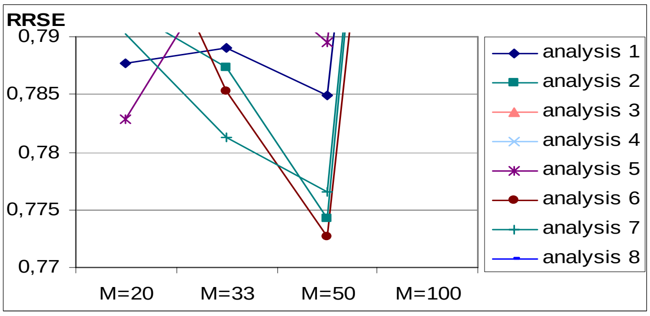


Figure B3 *Overview of RRSE values as indicators of the quality of models generated on different sets of attributes (analyses 1-8) and with different degrees of pruning (M) of model trees (10x cross validation). The lower picture enlarges the part with the lowest RRSE values.*

Table B1 *The regression correlation coefficients (R^2; linear regression) of the attributes that were taking place in the selected models (analysis 6, M=50; p = 0,05). Asterisk denotes significant regression correlation coefficients. Highest regression correlation coefficients that were found within individual group of attributes (e.g. among attributes describing minimal Ledava River levels, amounts of precipitation, etc.) are noted for comparison. Attributes that are written in bold took place in the model that was selected as the most reliable within individual group of attributes.*

attribute	**R^2**	**Highest R^2 within category**
age	*-0,62**	*age*
thinn	*-0,40**	*thinn*
thinn y-1	*-0,15*	*(thinn: -0,40)*
minL7	*-0,61**	*(minL5-8: -0,69)*
minL8	*-0,58**	*(minL5-8: -0,69)*
minL8-10	*-0,65**	*(minL5-8: -0,69)*
minL5-8	*-0,69**	*minL5-8*
minL5-9	*-0,68**	*(minL5-8: -0,69)*
maxL8	*-0,27*	*(maxL6: -0,37)*
maxL5-7	*-0,20*	*(maxL6: -0,37)*
averL4-7	*-0,60**	*(averL4-10: -0,66)*
t-sun4-7	*-0,39**	*(tsun4-9: -0,44)*
t-sun4-9	*-0,44**	*t-sun4-9*
minT4-10	*-0,12*	*(minT8-10: -0,24)*
precip7	*0,23*	*precip7*
d-wf4-7	*-0,40**	*(d-wf5: 0,485)*

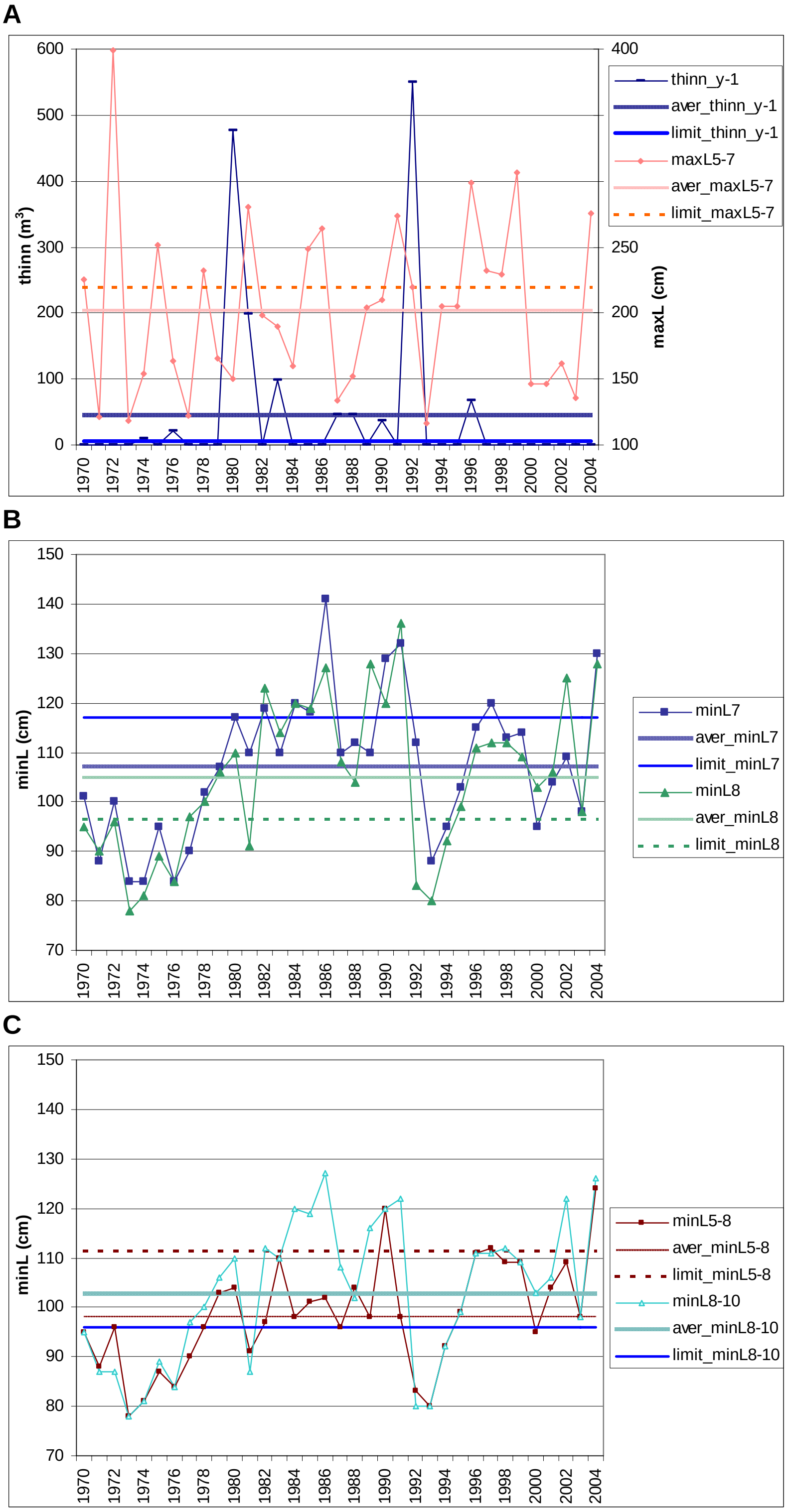


***Figure B4** The review on the values of attributes that were set as delimiting in the selected model trees, annual measured values of those attributes, and their average values. A: Volumes removed during the thinning in the previous year (thinn_y-1) and the values of the maximal Ledava River levels between May and July (maxL5-7). B: The minimal Ledava River levels in July (minL7) and in August (minL8). C: The minimal Ledava River levels between May and August and between August and October (minL5-8, minL8-10).*

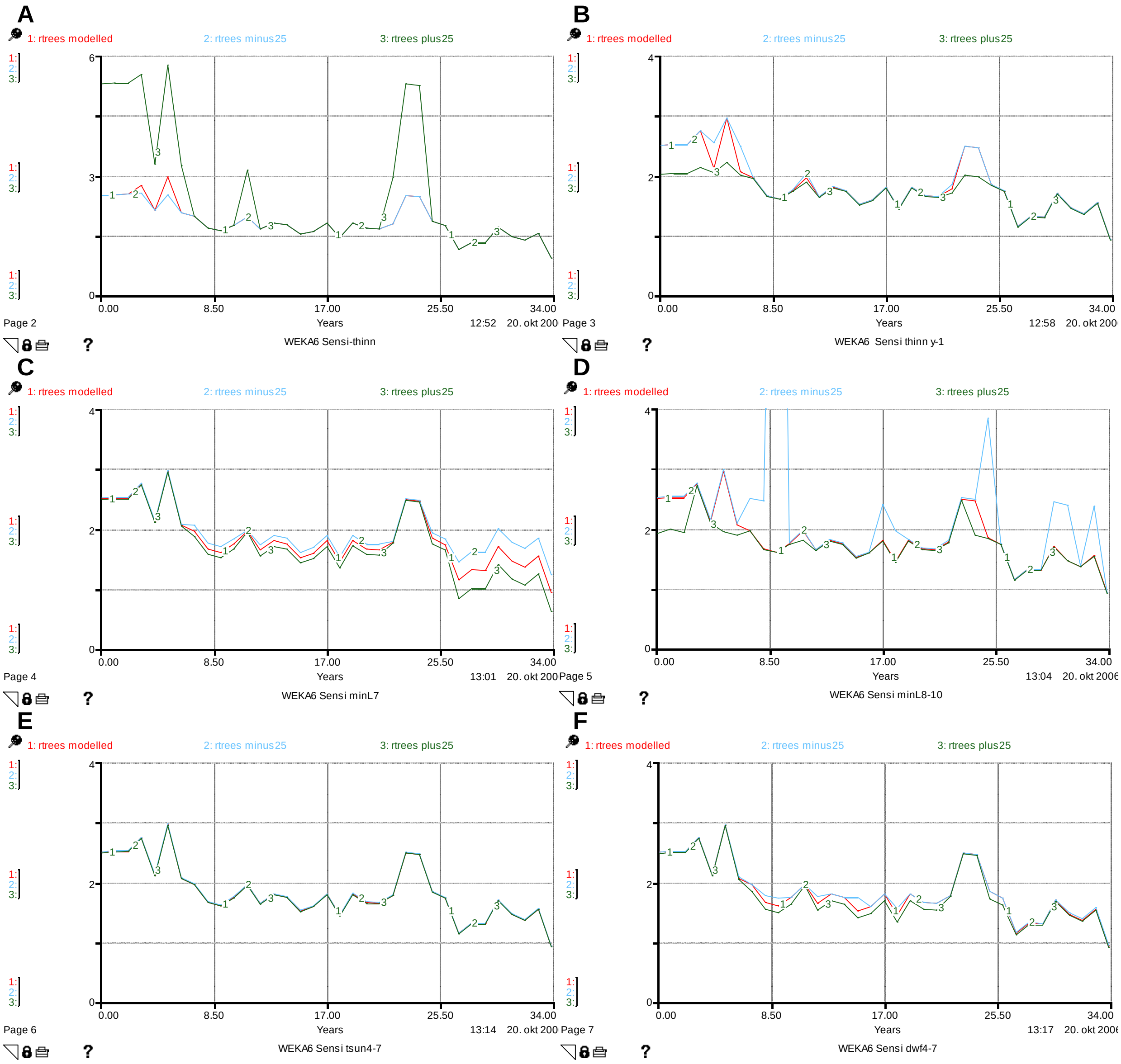
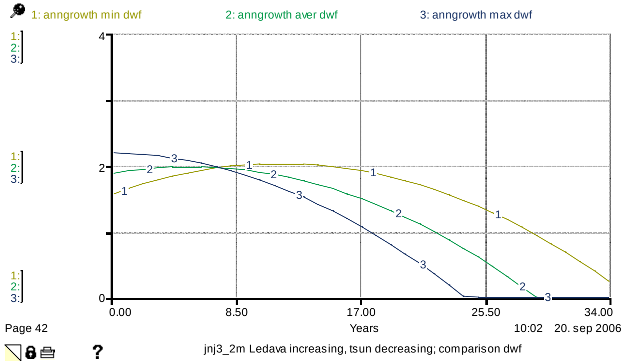


Figure B5 *Effects of increased and decreased values of individual attributes. The annual values of attributes were increased and decreased for 25% of the observed span of measured values. The figures present changes in annual increments when we varied:* ***A****: thinning in the current year (before the growing season) (thinn);* ***B****: thinning in the previous year (thinn_y-1);* ***C****: the minimal Ledava River levels in July (minL7);* ***D****: the minimal Ledava River levels between August and October (minL8-10);* ***E****: the duration of sun radiation in the first part of the growing season (tsun4-7);* ***F****: number of days with white frost between April and July (dwf4-7).*

APPENDIX C1: Overview of the models generated by the equation discovery tool.

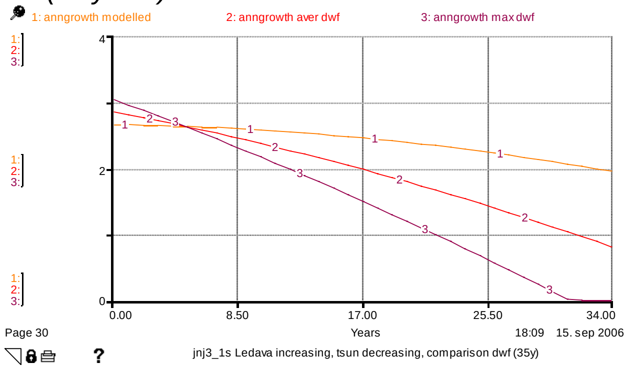
Jnj3_2m; A

B

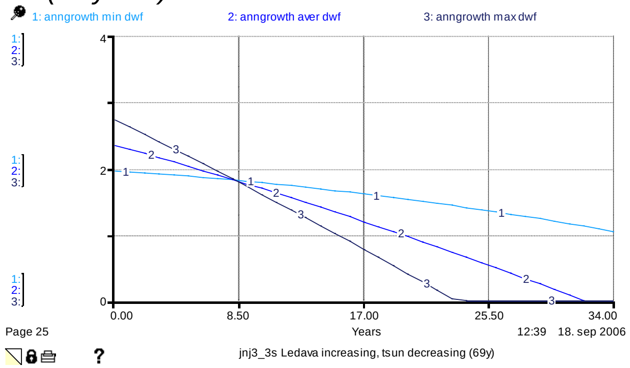


Jnj3_3s; A

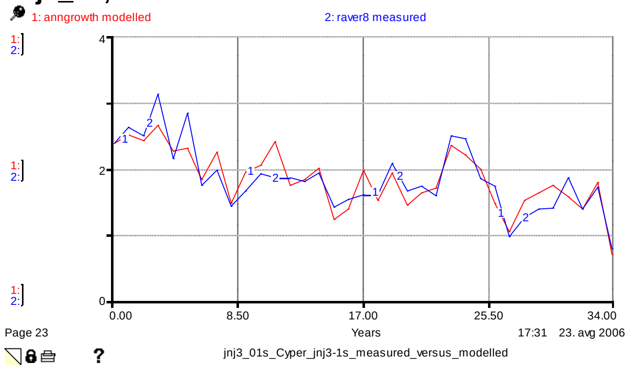
B1 (35 years)



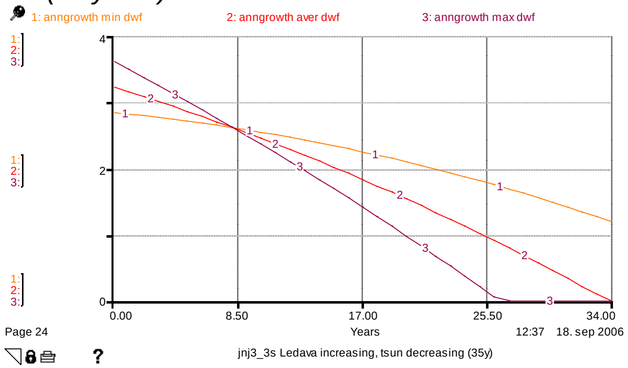
B2 (69 years)



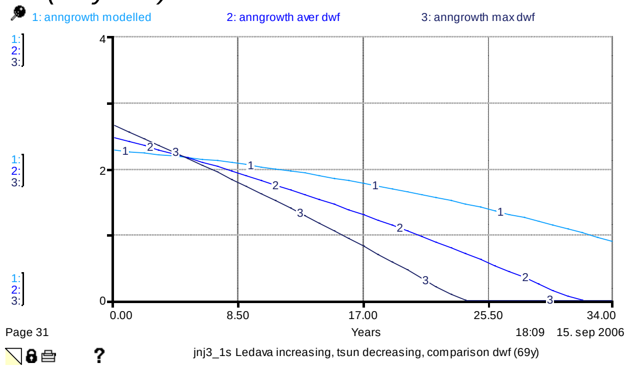
Jnj3_1s; A



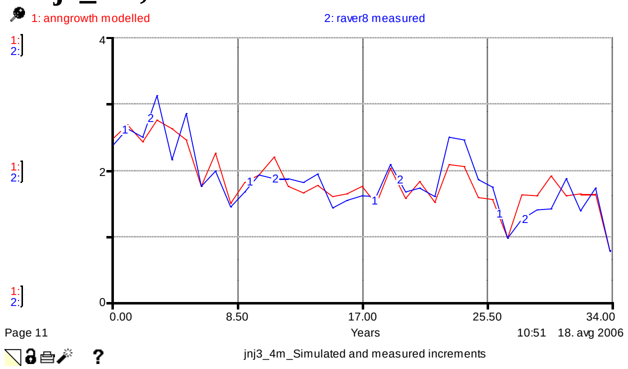
B1 (35 years)



B2 (69 years)

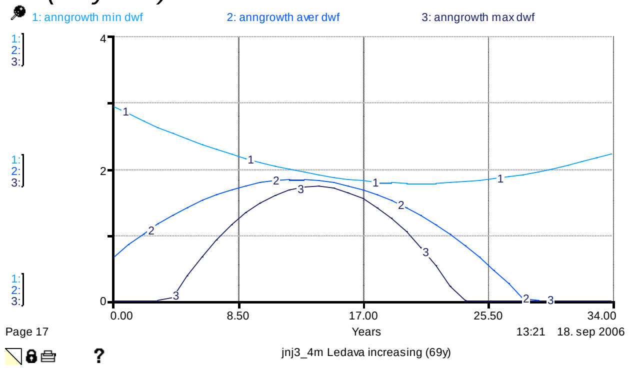


Jnj3_4m; A

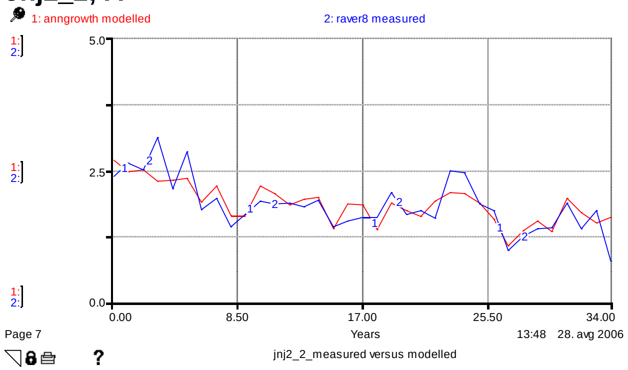


***B1** (35 years)*

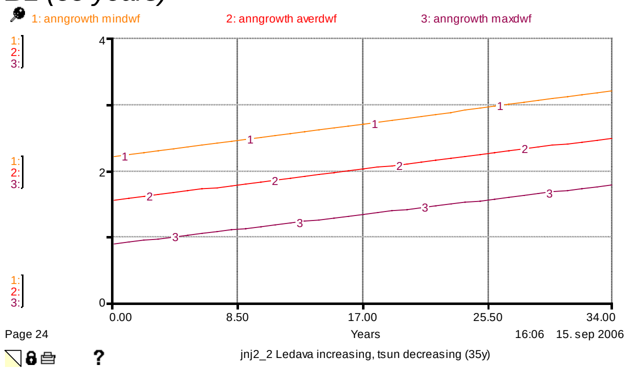
***B2** (69 years)*



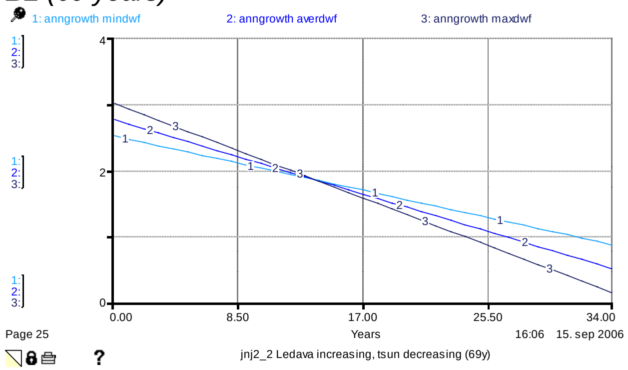
Jnj2_2; A



***B1** (35 years)*

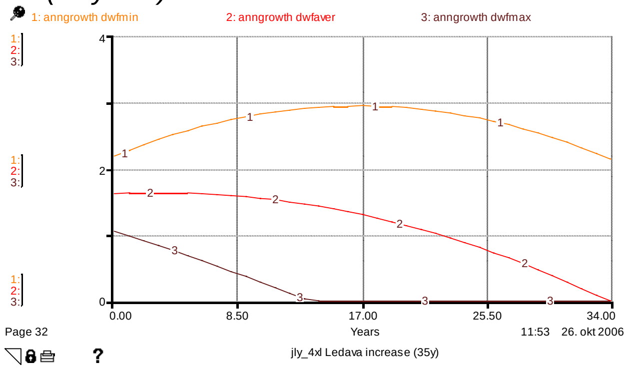


***B2** (69 years)*

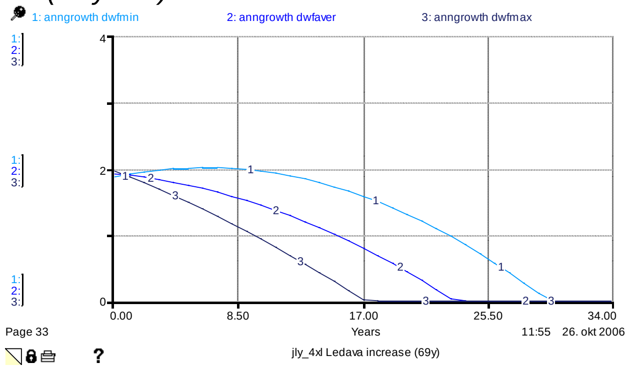


Jly_4xl*; A

***B1** (35 years)*

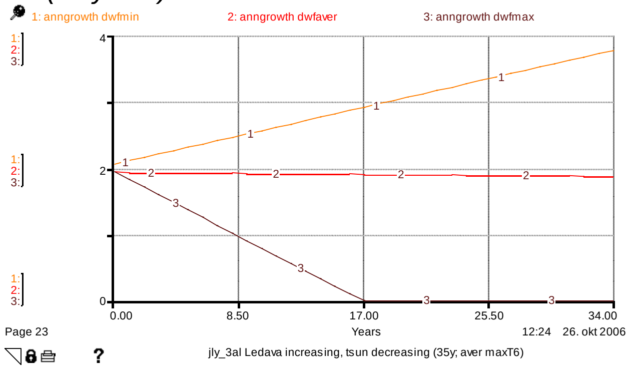


***B2** (69 years)*

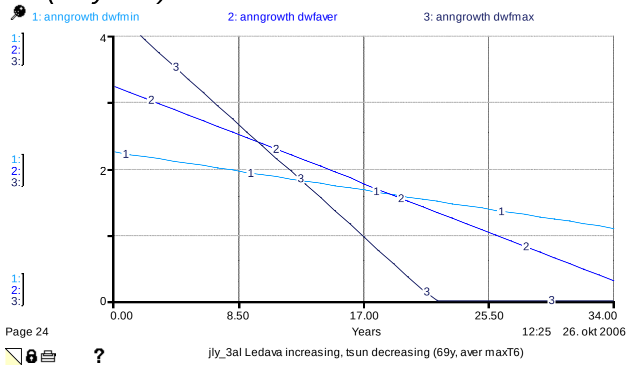


Jly_3al; A

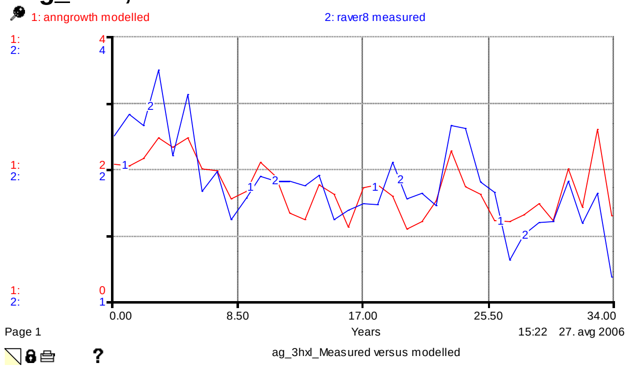
B1 (35 years)



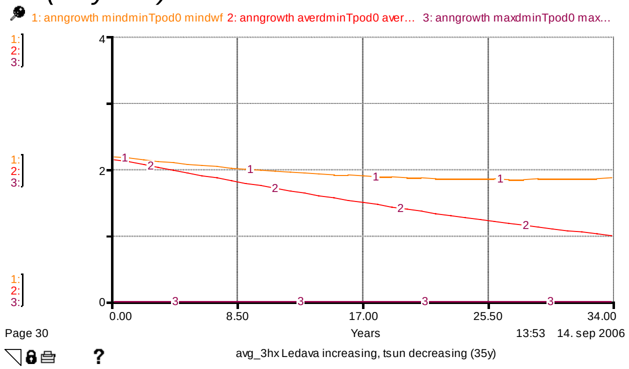
B2 (69 years)



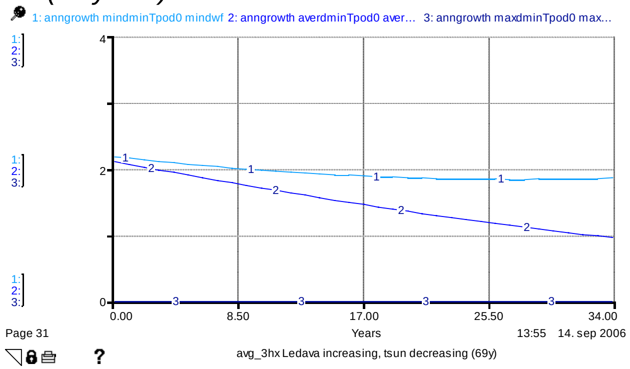
Avg_3hxl; A



B1 (35 years)

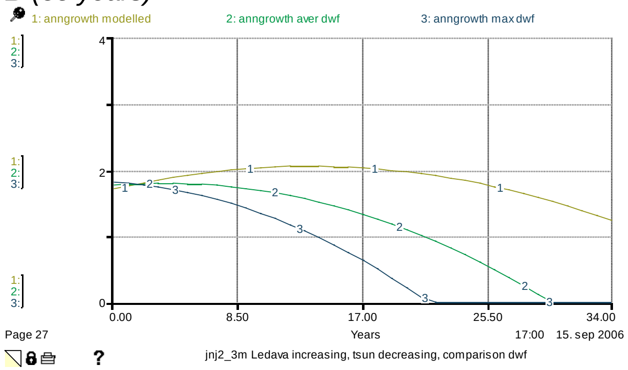


B2 (69 years)



Jnj2_3m; A

B (35 years)



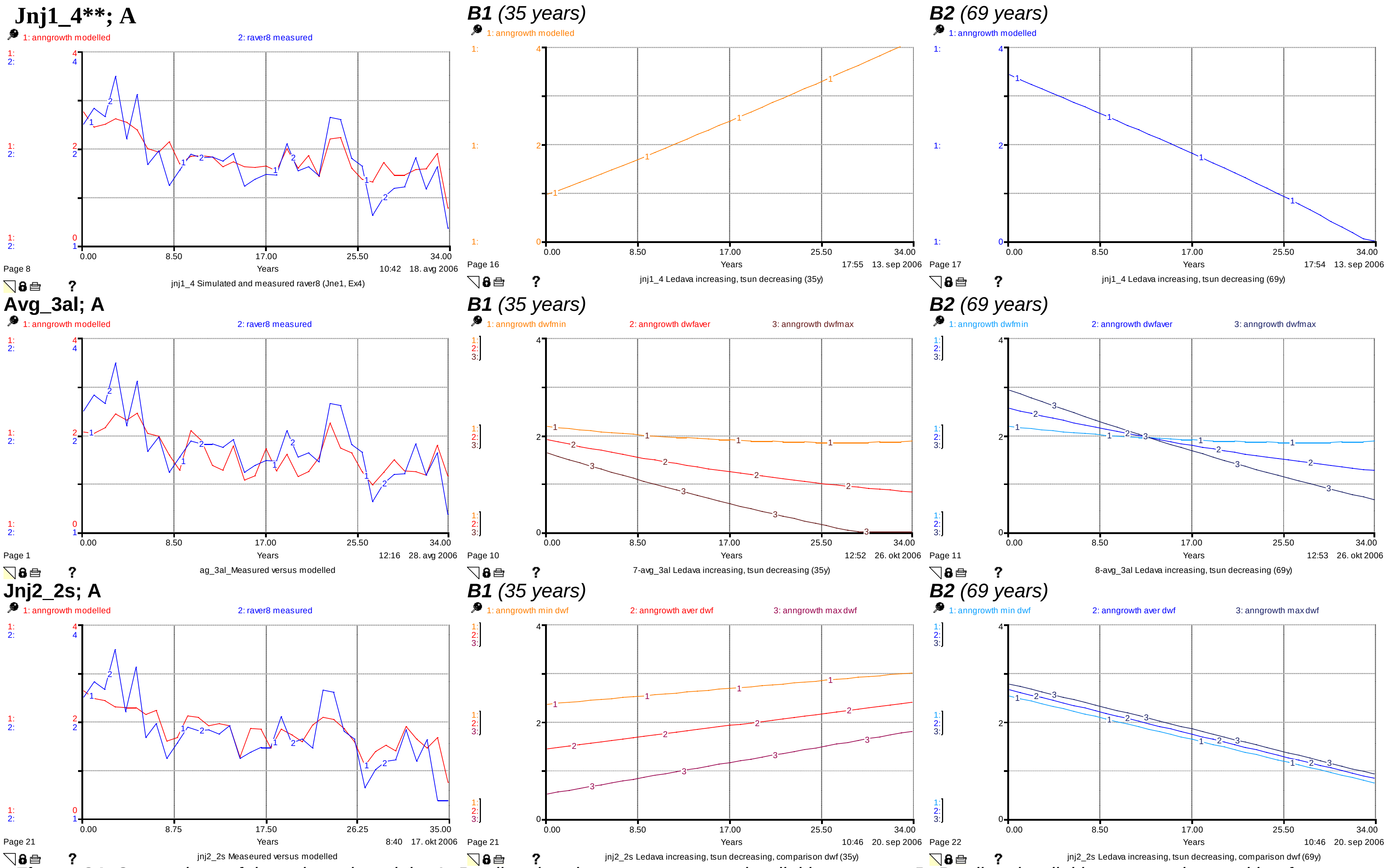


Figure C1 *Comparison of the selected models: A: Predicted and average measured radial increments. B: Predicted radial increments in transition from sunny and dry (left side of the graph) toward cloudy and wet years (right side of the graph) under three levels of white frost (curve 1: dwf4-7 = 0; 2: dwf4-7 = 2; and 3: dwf4-7 = 4).*
** t-sun was not identified as an important attribute in the model; *** dwf4-7 *was not identified as an important attribute in the model.*

The model jnj3_2m was overviewed in the Chapter 4.1.3.

The model jnj3_3s showed approximately linear decrease in radial increments under increasing levels of the Ledava River and decreasing duration of sun radiation (t-sun). Such a linear response means that radial increments were highest in the driest conditions. This is in contrary with the knowledge on tree physiology. Moreover the model predicted stimulative effects of number of days with white frost (d-wf4-7) under dry and sunny conditions, which cannot be explained. Problematic was also absence of increments in wet and cloudy conditions in years with frequent (4 days). Again, the most probable reason for this imperfection is low frequency of the data in years with numerous days with white frost. The increments were a bit lower at the age of 69 years than at the age of 35 years.

The model jnj3_1s showed a similar response as the model jnj3_3s. In comparison to the model jnj3_3s this model was a bit better with regard that the segments with stimulative effect of white frost as well as the segment with absent increments were a bit shorter.

The model jnj3_4m predicted highest increments in the extremely dry or in extremely wet years, when there was no white frost in the spring. Of course this was in the contrary to the physiological knowledge. On the other hand the model showed a very interesting response under frequent white frosts in the spring including low or absent increments. The effect of extremely numerous days with white frost was exaggerated in this model as well.

The model jnj2_2 showed a linear increase of radial increments with increasing cloudiness and wetness at the age of 35 years. The d-wf4-7 had diminishing effect on radial increments. This response was almost in agreement with our expectations. However, the response was just the opposite at the age of 69 years. At this age we observed positive effects of white frost in dry and sunny years once again.

The response of the model jly_4xl at the age of 35 years was similar to the response of the selected model (jnj3_2m). However, the increments were significantly decreased at the age of 69 years, together with totally absent increments under wet and cloudy conditions. In comparison to the selected model this one showed lower agreement with the measured data.

The model jly_3al showed linear responses. In years without white frost in the spring the response was opposite at the age of 35 years (positive effect of the River level increases) and at the age of 69 years (negative effect of the River level increases). D-wf4-7 was of crucial importance. Its effect was negative except in dry years at the age of 69 years.

The model avg_3hxl showed nearly identical response at both ages. In years without white frost the changes of the Ledava River levels and changes of t-sun were of minor importance. The model predicted destructive effect of numerous d-wf4-7 under all circumstances. Very high meaning was attributed to the appearance of white frost.

The behavior of the model jnj2_3m was relatively similar to the behavior of the selected model (jnj3_2m). Its equation did not include age. This model showed more reasonable behavior under higher d-wf4-7 than the model jnj3_2m, but it was less precise in predicting annual increments.

The equation of the model jnj1_4 did not contain the d-wf4-7 attribute. Consequently only one curve is presented for each age. We can see that the response to the increased Ledava River levels and decreased t-sun was just the opposite in both years.

The response of the model avg_3al was very similar at both ages if there was no white frost. However the response to white frost in the spring was quite different at both ages. Whereas it always had negative effect on annual increments at the age of 35 years, this was not the case in dry and sunny years at the age of 69 years. Highest increments were predicted in drought conditions.

The model jnj2_2s again belonged to the group of models in which responses were opposite at the age of 35 year and at the age of 69 years (e.g. models jnj2_2; jly_3al; jnj1_4) and the response was again approximately linear. Increases of d-wf4-7 had important negative effects at the age of 35 years, whereas the effect was surprisingly slightly positive at the age of 69 years. At the age of 35 years highest increments were predicted in the wettest years. On the contrary, the increments were predicted to be highest under driest and most sunny conditions at the age of 69 years.

APPENDIX C2: Overview of annual radial increments and values of selected attributes in those years

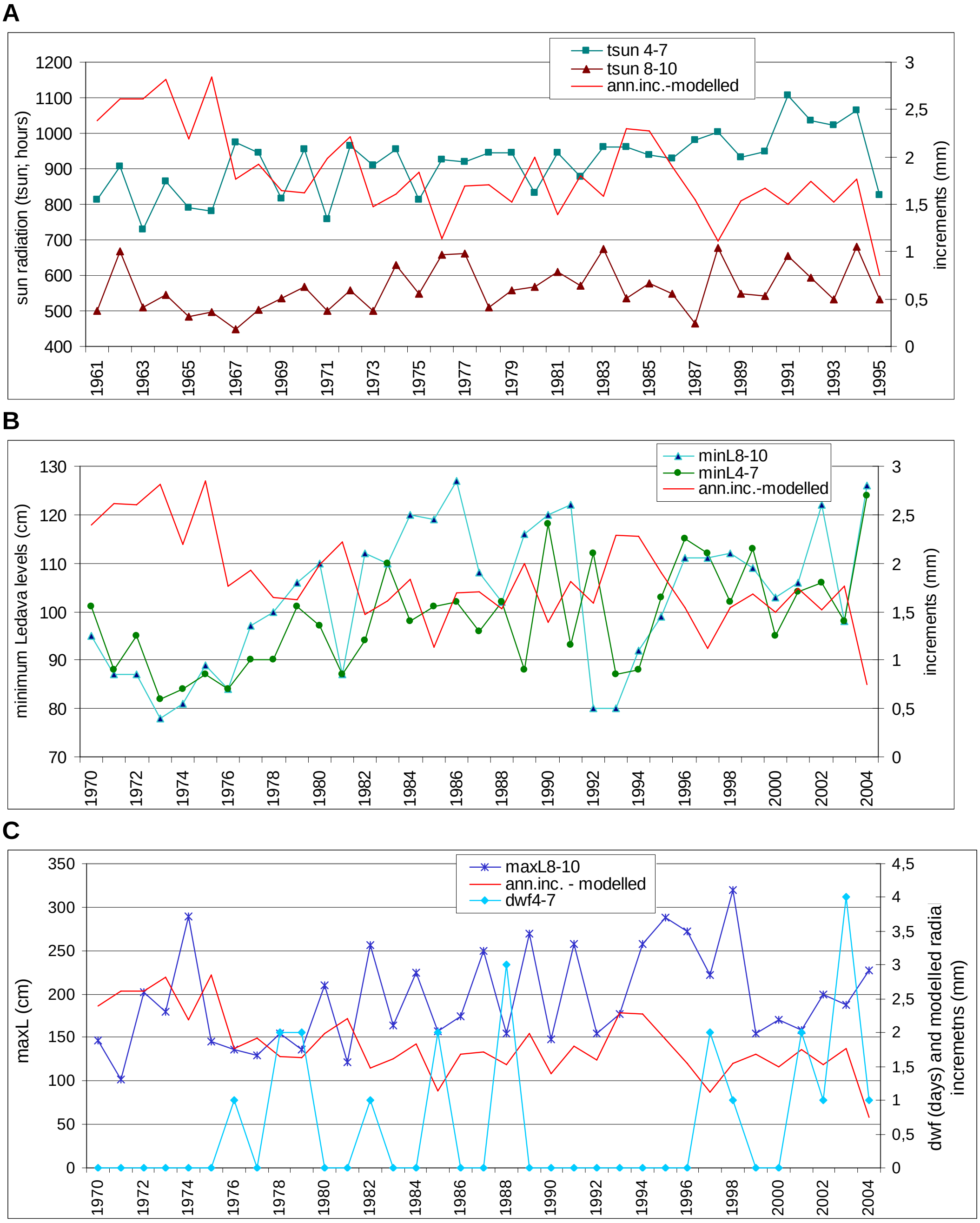
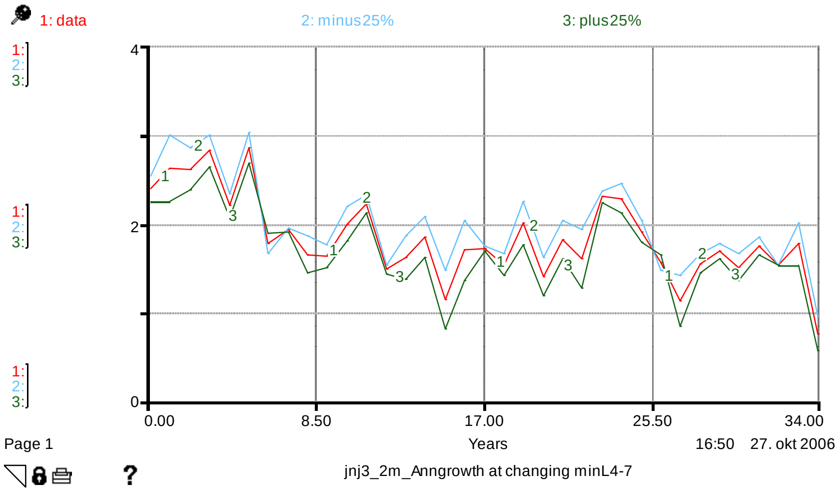


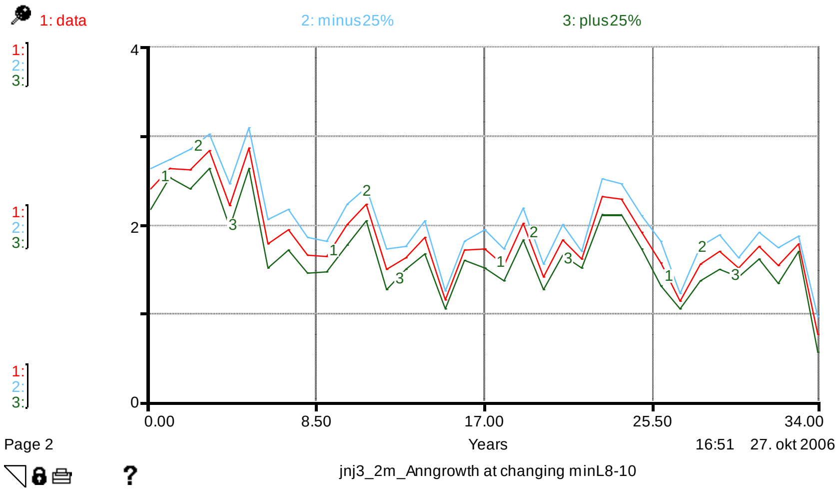
***Figure C1** The measured radial increments and attribute values. A: the data on sun radiation duration from April to July (tsun4-7) and from August to October (tsun8-10) and the data on measured average annual increments of eight trees (r-aver8). **B**: The data on the minimal Ledava River level between April and July (minL4-7), and between August and October (minL8-10); **C**: The data on the maximal Ledava level between August and October (maxL8-10), and the number of days with white frost between April and July (dwf4-7).*

APPENDIX C3: Additional sensitivity analyses of the model jnj3_2m

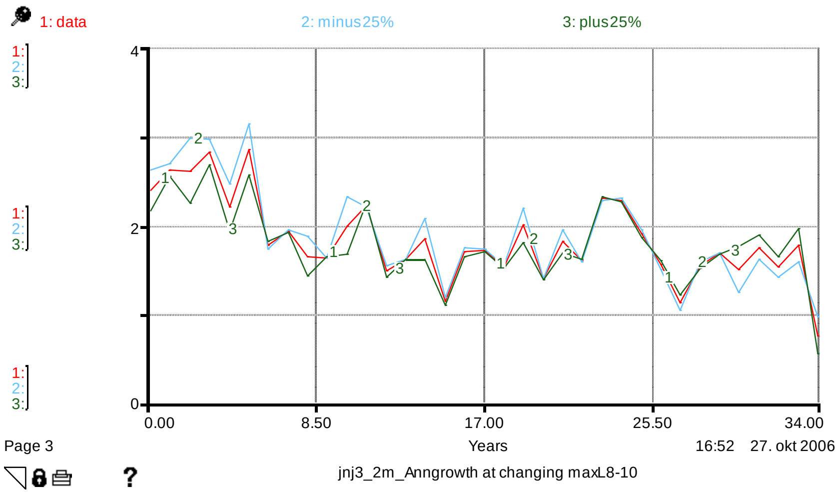
A



B



C



D

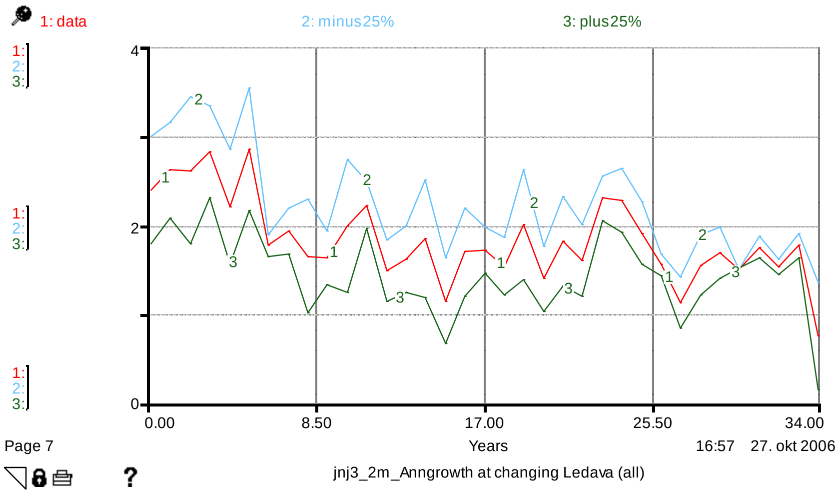
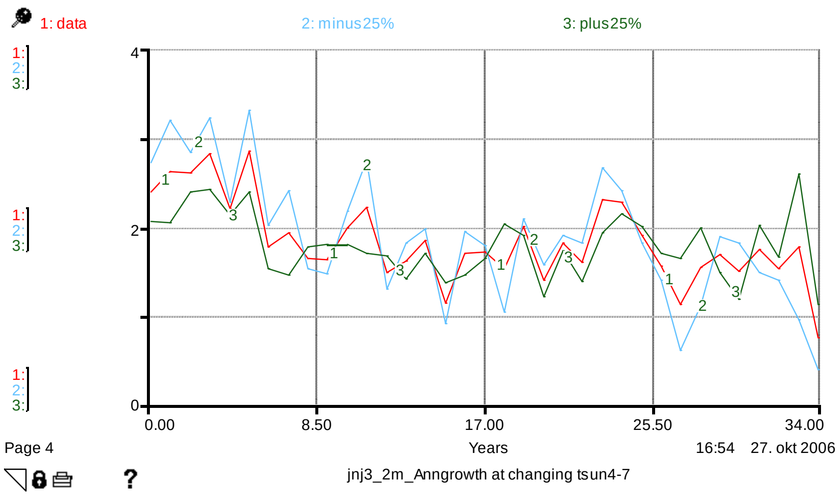


Figure C2 *Sensitivity analyses of the model jnj3_2m. Changes of predicted radial increments under original conditions (1), under decreased (2) and increased (3) attributes describing the Ledava River levels. The Ledava River levels were changed for 25% of the observed data range.* ***A****: minL4-7 (the minimum Ledava River levels between April and July; cm).* ***B****: minL8-10 (the minimum Ledava River levels between August and October; cm).* ***C****: maxL8-10 (the maximum Ledava River levels between August and October; cm).* ***D****: all Ledava River levels (minL4-7, minL8-10, maxL8-10; cm).*

A



B

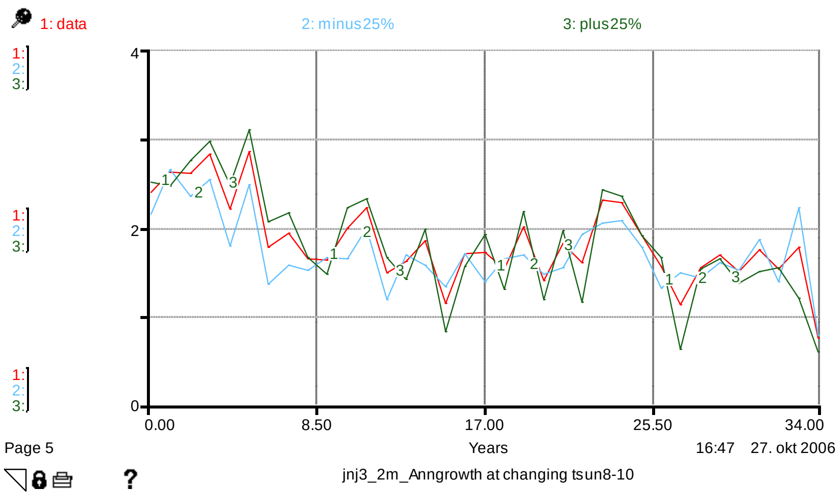


Figure C3 *Sensitivity analyses of the model jnj3_2m. Changes of predicted radial increments under original conditions (1), under decreased (2) and increased (3) individual attributes describing duration of sun radiation. The attributes were changed for 25% of the observed data range.* ***A****: tsun4-7 (the duration of sun radiation between April and July; hours);* ***B****: tsun8-10 (the duration of sun radiation between August and October; hours).*

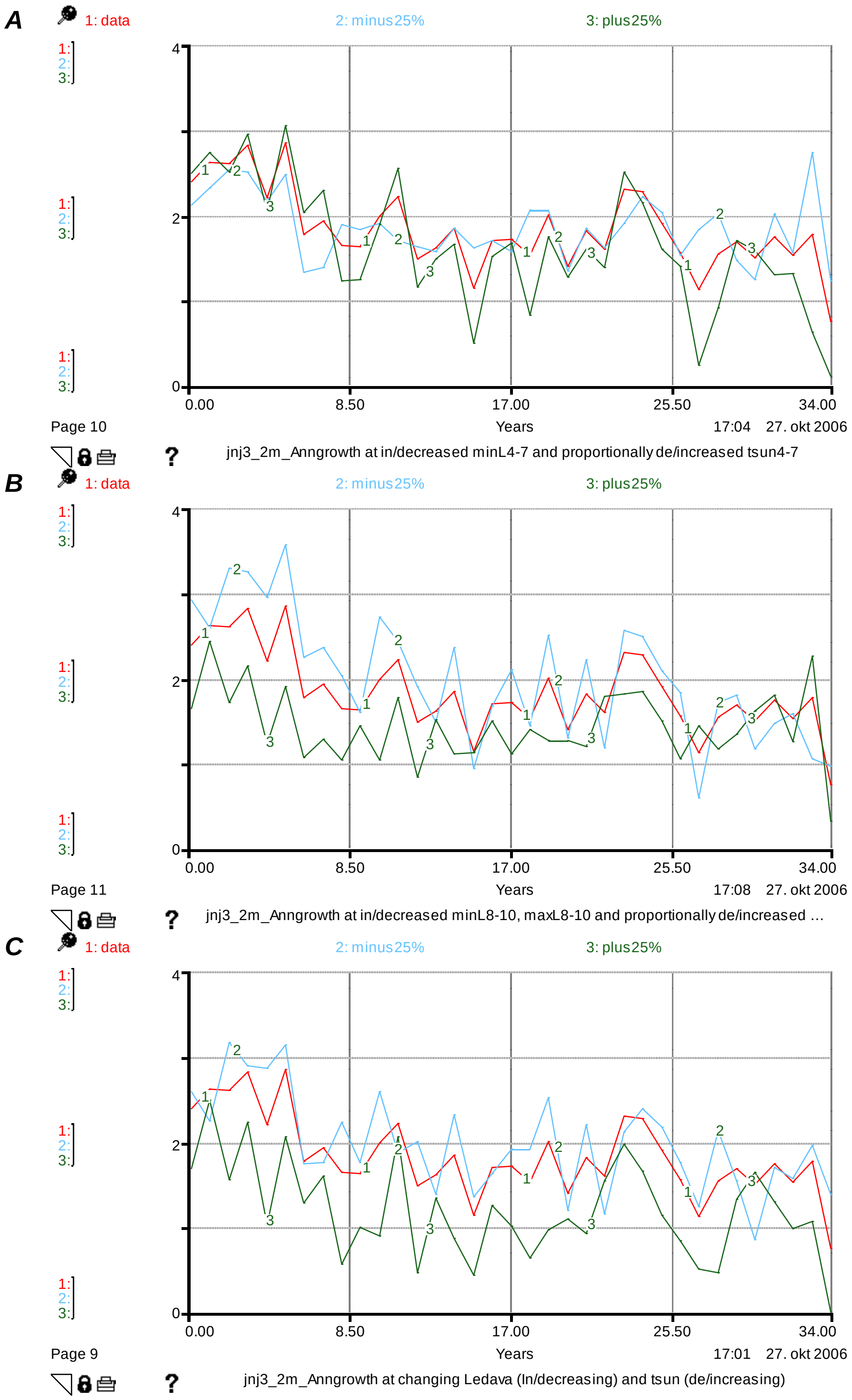
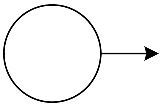


***Figure C4** Sensitivity analyses of the model jnj3_2m. Changes of the predicted radial increments under original conditions (1), under both decreased Ledava River levels and increased duration of sun radiation (2) and vice versa (3). The attributes were changed for 25% of the observed data range. **A**: minL4-7 (the minimum Ledava Level between April and July; cm) and tsun4-7 (the duration of sun radiation between April and July hours). **B**: MinL8-10, maxL8-10 (the minimum and maximum Ledava levels between August and October) and tsun8-10 (the duration of sun radiation between August and October; hours). **C**: all Ledava levels (minL4-7, minL8-10, maxL8-10; cm) and duration of sun radiation during the growing season (tsun4-7, tsun8-10; hours).*

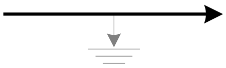
APPENDIX D: Symbols used in system diagrams

(Odum, 1996)

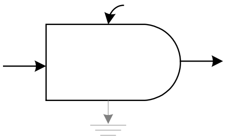
Enery circuit: A pathway whose flow is proportional to the quantity in the storage of source upstream.



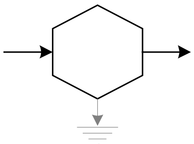
Source: Outside source of energy delivering forces or flows according to a program controlled from outside; a forcing function.



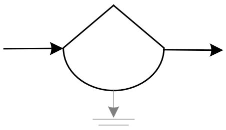
Heat sink: Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.



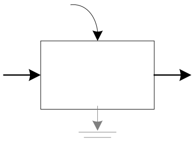
Producer: Unit that collects and transforms low-quality energy under control interactions of high-quality flows.



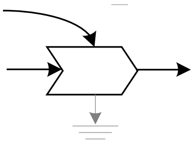
Consumer: Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.



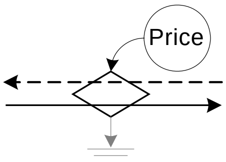
Tank: A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.



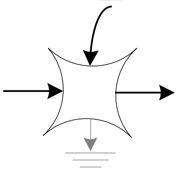
Box: Miscellaneous symbol to use for whatever unit or function is labeled.



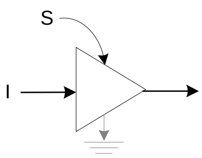
Interaction: Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both: control action of one flow on another; limiting factor action; work gate.



Transaction: A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is determined as external source.



Switching action: A symbol that indicates one or more switching actions.



Constant-gain amplifier: A unit that delivers an output in proportion to the input I but is changed by a constant factor as long as the energy source S is sufficient.

APPENDIX E: Emergy synthesis of Slovenia

Table E1: *Emergy Evaluation of Resource Basis for Slovenia.*

Note	Item	Raw Units		UEV (sej/unit)*	Solar Emergy (E+20 seJ)	EmDollars (E+09 USD)
RENEWABLE RESOURCES:						
1	Sunlight	6,62E+19	J	1	0,66	0,0
2	Rain, chemical	1,26E+17	J	18188	22,97	0,4
3	Rain, geopotential	3,47E+16	J	10000	3,46	0,1
4	Wind, kinetic energy	5,02E+16	J	1496	0,75	0,0
5	Waves	5,11E+14	J	31000	0,16	0,0
6	Tide	3,51E+14	J	17000	0,06	0,0
7	Earth Cycle	2,94E+16	J	34000	10,0	0,0
INDIGENOUS RENEWABLE ENERGY:						
8	Hydroelectricity	1,18E+16	J	3,36E+05	39,49	0,7
9	Agriculture Production	2,20E+16	J	3,36E+05	73,97	1,2
10	Livestock Production	1,89E+15	J	3,36E+06	63,59	1,1
11	Fisheries Production	1,21E+13	J	3,36E+06	0,41	0,0
12	Wood Production	1,60E+16	J	2,21E+04	3,53	0,1
NONRENEWABLE SOURCES FROM WITHIN SYSTEM:						
14	Natural Gas	2,10E+14	J	4,80E+04	0,10	0,0
15	Oil	4,36E+13	J	6,60E+04	0,03	0,0
16	Coal	4,89E+16	J	4,00E+04	19,56	0,3
17	Limestone and fertilizers	1,53E+13	g	1,78E+09	271,33	4,5
18	Metals	1,00E+06	g	1,68E+09	0,00002	0,0
19	Soil losses	1,46E+12	g	1,68E+09	24,54	0,4
20	Topsoil losses	9,91E+14	J	7,40E+04	0,73	0,0
IMPORTS AND OUTSIDE SOURCES:						
21	Fuels	3,71E+17	J	8,45E+04	313,62	5,2
22	Metals	1,81E+12	g	6,67E+09	120,70	2,0
23	Minerals	1,53E+12	g	2,30E+09	35,30	0,6
24	Nuclear fuel	6,78E+15	J	9,65E+04	6,54	0,1
25	Food and agricultural products	3,00E+16	J	3,36E+05	100,71	1,7
26	Livestock, meat, fish	1,83E+14	J	3,36E+06	6,15	0,1
27	Plastics and rubber	1,26E+16	J	1,11E+05	13,98	0,2
28	Chemicals	9,76E+11	g	1,48E+10	144,48	2,4
29	Finished materials	1,82E+12	g	2,52E+09	45,92	0,8
30	Machinery and transport. equipment	6,47E+11	g	6,70E+09	43,33	0,7
31	Service in imports	1,74E+09	$	1,85E+12	32,12	0,5
32	Tourism	5,37E+08	$	1,85E+12	9,94	0,2
EXPORTS:						
32	Food and agricultural products	2,78E+16	J	3,36E+05	93,53	1,6
33	Livestock, meat, fish	9,15E+13	J	3,36E+06	3,07	0,1
34	Finished materials	3,70E+12	g	2,19E+09	81,04	1,4
35	Fuels	1,34E+15	J	9,95E+04	1,33	0,0
36	Electricity	4,07E+15	J	1,50E+05	6,10	0,1
37	Metals	9,01E+11	g	8,60E+09	77,50	1,3
38	Minerals	7,38E+11	g	1,00E+09	7,38	0,1
39	Chemicals	3,42E+12	g	1,48E+10	505,88	8,4
40	Machinery and transport. equipment	1,09E+12	g	6,70E+09	72,93	1,2
41	Plastics and rubber	1,22E+16	J	1,11E+05	13,57	0,2
42	Service in exports	2,23E+09	$	5,99E+12	133,47	2,2
43	Tourism	1,08E+09	$	5,99E+12	64,37	1,1

* UEVs based on total renewable emergy flow of 9,44E+24 seJ/yr

Table E2: *Indices using emergy for overview of Slovenia.*

Item	Name of Index	Expression	Quantity
1	Renewable emergy flow	R	2,64E+21
2	Flow from indigenous nonrenewable reserves	N	3,20E+22
3	Flow of imported emergy	F+G+P2I	8,73E+22
4	Total emergy inflows	R+N+F+G+P2I	1,22E+23
5	Total emergy used, U	N0+N1+R+F+G+P2I	1,22E+23
6	Total exported emergy	P1E	1,06E+23
7	Fraction emergy use derived from home sources	(NO+N1+R)/U	0,28
8	Imports minus exports	(F+G+P2I)-(N2+B+P1E)	-7,86E+22
9	Export to Imports	(N2+P1E)/(F+G+P2I)	1,90
10	Fraction used, locally renewable	R/U	0,02
11	Fraction of use purchased	(F+G+P2I)/U	0,72
12	Fraction imported service	P2I/U	0,03
13	Fraction of use that is free	(R+N0)/U	0,05
14	Ratio of concentrated to rural	(F+G+P2I+N1)/(R+N0)	20,91
15	Use per unit area, Empower Density	U/(area ha)	6,02E+16
16	Use per person	U/population	6,21E+16
17	Renewable carrying capacity	COUNTRY POPULATION =	1,96E+06
	at present living standard	(R/U) (population)	4,26E+04
18	Ratio of use to GNP, emergy/dollar ratio	P1=U/GNP	5,99E+12
19	Ratio of electricity to use	(el)/U	4%
20	Fuel use per person	fuel/population	1,60E+16
21	ELR	(N+F)/R	12,11
22	EYR	(U/F)	2,56
23	ESI	EYR/ELR	0,21
24	emergy density	Y/area	6,02E+12
25	energy use per person		3,64E+11
26	emergy use per person		6,21E+16
27	emergy intensity	U/GNP	5,99E+12

APPENDIX F1: Emergy evaluation table: Flows and storages in physical units

Table F1 *Emergy evaluation table: Flows or storages in physical units for 35 years under study.*
Purchased sources-produced: sources for planting and nurse including thinning; Purchased sources- cutting into pieces+bringing out: sources for wood removal; /y: annual flows; NPP includes both aboveground and belowground net primary production; water at stand average amount of water in the stand in individual years; gw: groundwater; 4-10: data for the growing season; minL: minimum Ledava River levels; averL: average Ledava River levels; calc const: calculated as a constant value). Calculations are given in the Appendix E5.

Note	Item	<1970	1970	1971	1972	1973	1974	1975
I	**Environmental sources:**							
R	1 ET_{oa} (J/ha/y)	9,27E+11	2,78E+10	2,36E+10	2,76E+10	2,26E+10	2,53E+10	2,24E+10
	1_a $ET_{oa;4\text{-}10}$ (J/ha/y)	6,44E+11	1,84E+10	1,72E+10	1,71E+10	1,39E+10	1,51E+10	1,61E+10
	2 Precipitation (J/ha/y)	1,29E+12	3,82E+10	2,77E+10	5,55E+10	4,06E+10	4,67E+10	3,38E+10
	2_a $\text{Precipitation}_{4\text{-}10}$ (J/ha/y)	8,90E+11	2,33E+10	1,60E+10	4,12E+10	3,02E+10	3,59E+10	2,56E+10
	3 Run-in of gw (J/ha/y)	0	0	0	0	0	0	0
	3_a Run-in of $gw_{4\text{-}10\ (minL)}$ (J/ha/y)	0	0	0	0	0	0	0
	3_b Run-in of $gw_{4\text{-}10\ (averL)}$ (J/ha/y)	0	0	0	0	0	0	0
	4 White-frost (J/ha/y)	0	0	0	0	0	0	0
N	5 Leached N (g/ha/y)	5,47E+06	1,79E+05	1,49E+05	1,64E+05	1,68E+05	1,84E+05	1,53E+05
F1	**Purchased sources - produced**							
	6 Plantings/y (J/ha/y)	4,61E+09	0	0	0	0	0	0
	7 Wood for roads/y (J/ha/y)	7,70E+09	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08
	8 Gravel for roads/y (g/ha/y)	1,87E+04	1,87E+04	1,87E+04	1,87E+04	1,87E+04	1,87E+04	1,87E+04
	9_a Machinery-standing/y (g/ha/y)	16,67	16,67	16,67	17,15	17,23	16,67	17,28
	10_a Petrol–standing/y (J/ha/y)	1,67E+10	6,58E+06	6,58E+06	6,58E+06	1,37E+07	6,58E+06	1,29E+07
	11_a Human work-standing/y (h/ha/y)	355,961	0,017	0,017	0,017	0,671	0,017	0,595
	12_a Services-standing/y (USD/ha/y)	2805,020	0,285	0,285	0,285	4,825	0,285	4,299
	Purchased sources - cutting into pieces+bringing out							
	9_b Machinery-removed (g/ha/y)	8,29E+03	0	0	0	29,125	0	63,050
	10_b Petrol- removed (J/ha/y)	6,12E+09	0	0	0	2,15E+07	0	4,67E+07
	11_b Human work- removed (h/ha/y)	155,929	0	0	0	0,506	0	1,110
	12_b Services- removed (USD/ha/y)	1,20E+03	0	0	0	3,930	0	8,609
Y1	**Annual flows**							
	13 Aboveground wood/y (J/ha/yr)	3,51E+12	8,06E+10	8,90E+10	9,11E+10	9,94E+10	8,29E+10	1,05E+11
	14 Leaves/y (g/ha/y)	1,94E+08	4,46E+06	4,93E+06	5,05E+06	5,51E+06	4,59E+06	5,80E+06
	15 NPP/y (J/ha/y)	1,59E+13	3,65E+11	4,03E+11	4,13E+11	4,50E+11	3,75E+11	4,75E+11
	16 Aboveground biomass/y (J/ha/y)	9,91E+12	2,28E+11	2,51E+11	2,57E+11	2,81E+11	2,34E+11	2,96E+11
	17_a N_2 fixed/y (g/ha/y)	8,28E+06	1,90E+05	2,10E+05	2,15E+05	2,35E+05	1,96E+05	2,47E+05
	17_b N mineralized/y (g/ha/y)	3,55E+06	8,16E+04	9,01E+04	9,22E+04	1,01E+05	8,39E+04	1,06E+05
	18 Run out/y (J/y)	3,46E+11	1,37E+10	2,13E+09	3,06E+10	1,60E+10	2,26E+10	1,07E+10
	18_a Run $\text{out/y}_{4\text{-}10(minL)}$ (J/y)	2,88E+11	4,91E+09	1,06E+08	2,36E+10	1,54E+10	2,13E+10	8,60E+09
	18_b Run $\text{out/y}_{4\text{-}10(averL)}$ (J/y)	3,39E+11	1,72E+09	2,95E+09	2,16E+10	1,74E+10	2,07E+10	8,30E+09
	18_c Run $\text{out/y}_{4\text{-}10(calc\ const)}$ (J/y)	1,36E+11	3,55E+09	2,44E+09	6,29E+09	4,62E+09	5,48E+09	3,91E+09
Q1	**Stored quantities**							
	19 Water at stand (J/ha)	6,42E+10	6,48E+10	6,15E+10	6,34E+10	6,07E+10	6,27E+10	6,15E+10
	19_a Water at $\text{stand}_{4\text{-}10(minL)}$ (J/ha)	6,06E+10	6,04E+10	5,92E+10	5,92E+10	5,78E+10	5,83E+10	5,92E+10
	19_b Water at $\text{stand}_{4\text{-}10(averL)}$ (J/ha)	6,42E+10	6,37E+10	6,10E+10	6,42E+10	6,00E+10	6,24E+10	6,13E+10
	20 Standing wood (J/ha)	1,62E+12	1,70E+12	1,79E+12	1,88E+12	1,97E+12	2,06E+12	2,15E+12
	21 Total standing biomass (J/ha)	2,60E+12	2,74E+12	2,88E+12	3,03E+12	3,18E+12	3,31E+12	3,47E+12
	22 Organic matter in the soil (J/ha)	2,95E+14	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12
Y2	**Final products**							
	23 Removed wood/y (J/ha/yr)	1,89E+12	0	0	0	4,22E+09	0	9,29E+09
CUMULATIVE VALUES								
	13_{cum} Aboveground wood (J/ha)	3,51E+12	3,59E+12	3,68E+12	3,77E+12	3,87E+12	3,95E+12	4,06E+12
	15_{cum} NNP (J/ha)	1,59E+13	1,63E+13	1,67E+13	1,71E+13	1,75E+13	1,79E+13	1,84E+13
	$17_{a\ cum}$ N_2 fixed (g/ha/y)	8,28E+06	8,47E+06	8,68E+06	8,90E+06	9,13E+06	9,33E+06	9,58E+06
	24_{cum} Removed wood (J/ha)	1,89E+12	1,89E+12	1,89E+12	1,89E+12	1,89E+12	1,89E+12	1,90E+12

Table F1 – continued 1

Note	Item	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
I											
R	1	2,55E+10	2,84E+10	2,41E+10	2,75E+10	2,60E+10	2,52E+10	2,69E+10	2,88E+10	2,62E+10	2,69E+10
	1_a	1,65E+10	1,68E+10	1,61E+10	1,88E+10	1,78E+10	1,60E+10	1,86E+10	2,14E+10	1,89E+10	1,96E+10
	2	3,91E+10	3,15E+10	3,14E+10	4,28E+10	4,46E+10	3,35E+10	4,65E+10	2,81E+10	3,84E+10	4,03E+10
	2_a	2,65E+10	1,70E+10	2,27E+10	2,38E+10	3,15E+10	2,42E+10	3,49E+10	1,97E+10	2,55E+10	2,26E+10
	3	0	0	0	0	0	0	0	6,37E+08	0	0
	3_a	0	1,48E+09	0	0	0	0	0	2,09E+09	0	0
	3_b	0	0	0	0	0	0	0	1,42E+09	0	0
	4	1,07E+10	0	2,10E+10	1,93E+10	0	0	8,91E+09	0	0	1,52E+10
N	5	1,94E+05	1,34E+05	1,46E+05	1,31E+05	1,21E+05	1,38E+05	1,54E+05	1,11E+05	1,20E+05	1,35E+05
F1											
	6	0	0	0	0	0	0	0	0	0	0
	7	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08
	8	1,87E+04	1,87E+04	1,87E+04	1,87E+04	1,87E+04	1,87E+04	1,87E+04	1,87E+04	1,87E+04	1,87E+04
	9_a	17,30	17,30	16,67	17,31	16,67	17,15	16,67	16,67	16,67	17,29
	10_a	6,58E+06	6,58E+06	6,58E+06	1,08E+07	1,14E+07	6,58E+06	1,19E+07	6,58E+06	6,58E+06	6,58E+06
	11_a	0,017	0,017	0,017	0,401	0,462	0,017	0,507	0,017	0,017	0,017
	12_a	0,285	0,285	0,285	2,948	3,372	0,285	3,687	0,285	0,285	0,285
	9_b	0	0	0	1207,256	552,512	0	270,849	0	0	0
	10_b	0	0	0	9,18E+08	4,12E+08	0	2,02E+08	0	0	0
	11_b	0	0	0	23,547	9,946	0	4,915	0	0	0
	12_b	0	0	0	180,700	76,952	0	37,995	0	0	0
Y1											
	13	7,26E+10	7,89E+10	7,08E+10	6,53E+10	7,49E+10	8,32E+10	6,01E+10	6,51E+10	7,33E+10	5,14E+10
	14	4,02E+06	4,37E+06	3,92E+06	3,62E+06	4,15E+06	4,61E+06	3,33E+06	3,61E+06	4,06E+06	2,85E+06
	15	3,29E+11	3,57E+11	3,20E+11	2,96E+11	3,39E+11	3,77E+11	2,72E+11	2,95E+11	3,32E+11	2,33E+11
	16	2,05E+11	2,23E+11	2,00E+11	1,84E+11	2,11E+11	2,35E+11	1,70E+11	1,84E+11	2,07E+11	1,45E+11
	17_a	1,71E+05	1,86E+05	1,67E+05	1,54E+05	1,77E+05	1,97E+05	1,42E+05	1,54E+05	1,73E+05	1,21E+05
	17_b	7,34E+04	7,98E+04	7,16E+04	6,61E+04	7,57E+04	8,42E+04	6,08E+04	6,59E+04	7,42E+04	5,20E+04
	18	1,23E+10	3,91E+09	6,09E+09	1,48E+10	2,10E+10	5,07E+09	2,02E+10	0	1,15E+10	1,23E+10
	18_a	1,01E+10	0	7,26E+09	6,49E+09	1,26E+10	5,85E+09	1,82E+10	0	6,43E+09	3,94E+09
	18_b	9,53E+09	5,47E+07	5,71E+09	6,88E+09	1,02E+10	8,61E+09	1,67E+10	0	5,33E+09	4,98E+09
	18_c	4,05E+09	2,60E+09	3,47E+09	3,63E+09	4,80E+09	3,70E+09	5,33E+09	3,01E+09	3,89E+09	3,45E+09
Q1											
	19	6,21E+10	6,34E+10	6,27E+10	6,39E+10	6,43E+10	6,19E+10	6,52E+10	6,46E+10	6,46E+10	6,54E+10
	19_a	5,87E+10	5,96E+10	5,96E+10	6,13E+10	6,07E+10	5,92E+10	6,02E+10	6,27E+10	6,08E+10	6,13E+10
	19_b	6,15E+10	6,27E+10	6,32E+10	6,34E+10	6,43E+10	6,24E+10	6,59E+10	6,55E+10	6,51E+10	6,49E+10
	20	2,23E+12	2,30E+12	2,38E+12	2,25E+12	2,24E+12	2,32E+12	2,34E+12	2,41E+12	2,48E+12	2,53E+12
	21	3,58E+12	3,71E+12	3,82E+12	3,62E+12	3,61E+12	3,74E+12	3,77E+12	3,88E+12	3,99E+12	4,08E+12
	22	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12
Y2											
	23	0	0	0	2,01E+11	8,36E+10	0	4,14E+10	0	0	0

CUMULATIVE VALUES

13_{cum}	4,13E+12	4,21E+12	4,28E+12	4,34E+12	4,42E+12	4,50E+12	4,56E+12	4,63E+12	4,70E+12	4,75E+12
15_{cum}	1,87E+13	1,91E+13	1,94E+13	1,97E+13	2,00E+13	2,04E+13	2,07E+13	2,10E+13	2,13E+13	2,15E+13
$17_{a\ cum}$	9,75E+06	9,94E+06	1,01E+07	1,03E+07	1,04E+07	1,06E+07	1,08E+07	1,09E+07	1,11E+07	1,12E+07
24_{cum}	1,90E+12	1,90E+12	1,90E+12	2,11E+12	2,19E+12	2,19E+12	2,23E+12	2,23E+12	2,23E+12	2,23E+12

Table F1 – continued 2

Note	Item	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
I											
R	1	2,70E+10	2,63E+10	2,77E+10	2,70E+10	2,84E+10	2,68E+10	2,93E+10	2,27E+10	2,88E+10	2,76E+10
	1_a	1,98E+10	1,83E+10	1,82E+10	1,75E+10	2,27E+10	1,90E+10	1,91E+10	1,57E+10	1,63E+10	1,96E+10
	2	3,90E+10	4,61E+10	3,49E+10	3,54E+10	3,77E+10	4,21E+10	3,36E+10	3,98E+10	4,16E+10	4,16E+10
	2_a	2,45E+10	3,07E+10	2,37E+10	3,02E+10	2,47E+10	2,76E+10	2,11E+10	2,55E+10	3,20E+10	2,49E+10
	3	0	0	0	0	0	0	0	0	0	0
	3_a	0	0	0	0	0	0	0	0	0	0
	3_b	0	0	0	0	0	0	1E+09	0	0	0
	4	0	0	2,91E+10	0	0	0	0	0	0	0
N	5	9,49E+04	1,29E+05	1,31E+05	1,21E+05	1,51E+05	1,15E+05	1,32E+05	1,21E+05	1,66E+05	1,68E+05
F1											
	6	0	0	0	0	0	0	0	0	0	0
	7	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08
	8	3,93E+05	3,93E+05	3,93E+05	3,93E+05	3,93E+05	3,93E+05	3,93E+05	3,93E+05	3,93E+05	3,93E+05
	9_a	17,301	17,301	16,670	17,310	16,670	17,149	16,670	16,670	16,670	17,290
	10_a	1,21E+07	1,21E+07	6,58E+06	1,21E+07	6,58E+06	1,08E+07	6,58E+06	6,58E+06	6,58E+06	1,20E+07
	11_a	0,521	0,521	0,017	0,529	0,017	0,400	0,017	0,017	0,017	0,513
	12_a	3,786	3,786	0,285	3,837	0,285	2,946	0,285	0,285	0,285	3,727
	9_b	127,997	127,563	0	99,729	0	1332,919	0	0	0	180,034
	10_b	9,58E+07	9,56E+07	0	7,48E+07	0	1,02E+09	0	0	0	1,36E+08
	11_b	2,351	2,350	0	1,848	0	26,979	0	0	0	3,387
	12_b	18,154	18,139	0	14,255	0	206,300	0	0	0	26,083
Y1											
	13	6,96E+10	7,07E+10	6,56E+10	8,19E+10	6,22E+10	7,15E+10	6,54E+10	8,99E+10	9,09E+10	7,88E+10
	14	3,86E+06	3,92E+06	3,63E+06	4,54E+06	3,45E+06	3,96E+06	3,62E+06	4,98E+06	5,03E+06	4,37E+06
	15	3,15E+11	3,20E+11	2,97E+11	3,71E+11	2,82E+11	3,24E+11	2,96E+11	4,07E+11	4,11E+11	3,57E+11
	16	1,97E+11	2,00E+11	1,85E+11	2,31E+11	1,76E+11	2,02E+11	1,85E+11	2,54E+11	2,57E+11	2,23E+11
	17_a	1,64E+05	1,67E+05	1,55E+05	1,93E+05	1,47E+05	1,69E+05	1,54E+05	2,12E+05	2,15E+05	1,86E+05
	17_b	7,04E+04	7,15E+04	6,63E+04	8,29E+04	6,29E+04	7,24E+04	6,62E+04	9,09E+04	9,19E+04	7,97E+04
	18	1,40E+10	2,05E+10	7,38E+09	6,78E+09	7,99E+09	1,85E+10	6,89E+09	1,45E+10	1,09E+10	1,21E+10
	18_a	3,87E+09	1,45E+10	9,35E+08	1,64E+10	3,97E+09	8,65E+09	8,54E+08	8,14E+09	1,38E+10	5,29E+09
	18_b	5,43E+09	1,02E+10	4,56E+09	1,19E+10	6,21E+09	1,16E+10	0	8,70E+09	1,26E+10	7,42E+09
	18_c	3,75E+09	4,68E+09	3,61E+09	4,60E+09	3,78E+09	4,22E+09	3,22E+09	3,89E+09	4,88E+09	3,80E+09
Q1											
	19	6,64E+10	6,45E+10	6,37E+10	6,36E+10	6,52E+10	6,66E+10	6,34E+10	6,08E+10	6,34E+10	6,54E+10
	19_a	6,15E+10	6,05E+10	6,15E+10	5,93E+10	6,39E+10	6,01E+10	5,81E+10	5,81E+10	5,93E+10	6,10E+10
	19_b	6,62E+10	6,42E+10	6,36E+10	6,58E+10	6,67E+10	6,75E+10	6,33E+10	6,04E+10	6,34E+10	6,45E+10
	20	2,58E+12	2,63E+12	2,70E+12	2,77E+12	2,83E+12	2,67E+12	2,74E+12	2,83E+12	2,92E+12	2,97E+12
	21	4,16E+12	4,24E+12	4,35E+12	4,45E+12	4,55E+12	4,31E+12	4,41E+12	4,56E+12	4,70E+12	4,78E+12
	22	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12
Y2											
	23	1,98E+10	1,98E+10	0	1,56E+10	0	2,32E+11	0	0	0	2,87E+10

CUMULATIVE VALUES

13_{cum}	4,82E+12	4,89E+12	4,96E+12	5,04E+12	5,10E+12	5,17E+12	5,24E+12	5,33E+12	5,42E+12	5,50E+12
15_{cum}	2,18E+13	2,22E+13	2,25E+13	2,28E+13	2,31E+13	2,34E+13	2,37E+13	2,41E+13	2,45E+13	2,49E+13
$17_{a\ cum}$	1,14E+07	1,16E+07	1,17E+07	1,19E+07	1,20E+07	1,22E+07	1,24E+07	1,26E+07	1,28E+07	1,30E+07
24_{cum}	2,25E+12	2,27E+12	2,27E+12	2,29E+12	2,29E+12	2,52E+12	2,52E+12	2,52E+12	2,52E+12	2,55E+12

Table F1 – continued 3

Note	Item	1996	1997	1998	1999	2000	2001	2002	2003	2004
I										
R	1	2,63E+10	2,81E+10	2,82E+10	2,80E+10	3,08E+10	2,93E+10	3,86E+10	3,11E+10	2,71E+10
	1_a	2,11E+10	2,07E+10	1,91E+10	2,21E+10	2,11E+10	2,16E+10	2,94E+10	2,07E+10	2,23E+10
	2	5,05E+10	3,19E+10	4,19E+10	3,50E+10	2,74E+10	3,03E+10	3,31E+10	2,75E+10	4,25E+10
	2_a	3,74E+10	2,10E+10	3,31E+10	2,27E+10	1,86E+10	2,13E+10	2,65E+10	2,00E+10	3,01E+10
	3	0	0	0	0	4,42E+09	0	3,89E+09	7,46E+09	0
	3_a	0	6,60E+08	0	7,71E+08	2,75E+09	0	6,87E+09	0	0
	3_b	0	0	0	9,43E+08	3,48E+09	0	7,91E+09	0	0
	4	0	1,58E+10	1,02E+10	0	0	2,36E+10	1,07E+10	4,92E+10	6,52E+09
N	5	1,46E+05	1,25E+05	9,84E+04	1,28E+05	1,39E+05	1,28E+05	1,47E+05	1,34E+05	1,53E+05
F1										
	6	0	0	0	0	0	0	0	0	0
	7	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08	2,27E+08
	8	1,87E+04	1,87E+04	1,87E+04	1,87E+04	1,87E+04	1,87E+04	1,87E+04	1,87E+04	1,87E+04
	9_a	16,67	16,67	16,67	16,67	16,67	16,67	16,67	16,67	17,15
	10_a	6,58E+06	6,58E+06	6,58E+06	6,58E+06	6,58E+06	6,58E+06	6,58E+06	6,58E+06	6,58E+06
	11_a	0,017	0,017	0,017	0,017	0,017	0,017	0,017	0,017	0,399
	12_a	0,285	0,285	0,285	0,285	0,285	0,285	0,285	0,285	0,285
	9_b	0	0	0	0	0	0	0	0	20063,10
	10_b	0	0	0	0	0	0	0	0	1,55E+10
	11_b	0	0	0	0	0	0	0	0	415,851
	12_b	0	0	0	0	0	0	0	0	3172,708
Y1										
	13	6,76E+10	5,33E+10	6,92E+10	7,50E+10	6,95E+10	7,98E+10	7,25E+10	8,30E+10	4,40E+10
	14	3,74E+06	2,95E+06	3,83E+06	4,15E+06	3,85E+06	4,42E+06	4,02E+06	4,60E+06	2,44E+06
	15	3,06E+11	2,41E+11	3,13E+11	3,40E+11	3,15E+11	3,61E+11	3,28E+11	3,76E+11	1,99E+11
	16	1,91E+11	1,50E+11	1,95E+11	2,12E+11	1,96E+11	2,25E+11	2,05E+11	2,34E+11	1,24E+11
	17_a	1,60E+05	1,26E+05	1,63E+05	1,77E+05	1,64E+05	1,88E+05	1,71E+05	1,96E+05	1,04E+05
	17_b	6,84E+04	5,39E+04	7,00E+04	7,59E+04	7,03E+04	8,07E+04	7,33E+04	8,40E+04	4,45E+04
	18	2,58E+10	3,51E+09	1,40E+10	8,30E+09	0	5,30E+08	0	0	8,34E+10
	18_a	1,76E+10	0	1,62E+10	0	0	9,37E+08	0	6,41E+10	7,82E+09
	18_b	1,53E+10	1,48E+09	1,58E+10	0	0	2,75E+09	0	6,74E+10	7,82E+09
	18_c	5,71E+09	3,21E+09	5,06E+09	3,46E+09	2,84E+09	3,26E+09	4,04E+09	3,06E+09	4,59E+09
Q1										
	19	6,72E+10	6,55E+10	6,58E+10	6,55E+10	6,42E+10	6,52E+10	6,57E+10	6,40E+10	6,80E+10
	19_a	6,28E+10	6,28E+10	6,15E+10	6,25E+10	6,04E+10	6,18E+10	6,21E+10	6,08E+10	6,48E+10
	19_b	6,75E+10	6,54E+10	6,64E+10	6,53E+10	6,36E+10	6,51E+10	6,62E+10	6,31E+10	6,81E+10
	20	3,04E+12	3,09E+12	3,16E+12	3,24E+12	3,31E+12	3,39E+12	3,46E+12	3,54E+12	3,59E+12
	21	4,89E+12	4,98E+12	5,09E+12	5,21E+12	5,32E+12	5,45E+12	5,57E+12	5,70E+12	5,77E+12
	22	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12	8,68E+12
Y2										
	23	0	0	0	0	0	0	0	0	3,59E+12
CUMULATIVE VALUES										
	13_{cum}	5,57E+12	5,62E+12	5,69E+12	5,76E+12	5,83E+12	5,91E+12	5,99E+12	6,07E+12	6,11E+12
	15_{cum}	2,52E+13	2,54E+13	2,58E+13	2,61E+13	2,64E+13	2,68E+13	2,71E+13	2,75E+13	2,77E+13
	$17_{a\,cum}$	1,31E+07	1,33E+07	1,34E+07	1,36E+07	1,38E+07	1,40E+07	1,41E+07	1,43E+07	1,44E+07
	24_{cum}	2,55E+12	2,55E+12	2,55E+12	2,55E+12	2,55E+12	2,55E+12	2,55E+12	2,55E+12	6,13E+12

APPENDIX F2: Emergy evaluation table: UEVs for flows and storages

***Table F2** Emergy evaluation table: UEVs for flows and storages for 35 years under study.*
Constant values for UEVs that were adopted from previous studies or calculated in this study are written in the first column and the source of the data in written in the second column. All other UEVs were calculated in this study for each individual year. Data on harvested wood were calculated only for years in which harvesting took place.
/w: UEV calculated without purchased sources. For other notes see Table F1. Calculations are given in the Appendix E5.

Note	Item	<1970	1970	1971	1972	1973	1974	1975
I	**Environmental sources:**							
R	1 ET_{oa} (sej/J)	2,80E+04	(Brown, 1978)					
	1_a $ET_{oa\ 4\text{-}10}$ (sej/J)	2,80E+04	(Brown, 1978)					
	2 Precipitation (sej/J)	1,82E+04	(Odum, 1996)					
	3 Run-in of gw (sej/J)	6,15E+04	(this study)					
	3_a Run-in of $gw_{4\text{-}10}$ (sej/J)	1,71E+05	(this study)					
	4 White-frost (sej/J)	2,78E+03	(this study)					
N	5 Leached N (g/ha/y)	5,58E+08	5,13E+08	5,13E+08	5,12E+08	5,11E+08	5,08E+08	5,09E+08
F1	**Purchased sources**							
	6 Plantings (sej/J)		(this study see calculation)					
	7 Wood for roads (sej/J)	2,51E+04	(this study)					
	8 Gravel for roads (sej/g)	1,00E+09	(Odum, 1996)					
	9_a Machinery (sej/g)	6,70E+09	(Doherty, 1995)					
	10_a Petrol (sej/J)	4,79E+04	(Doherty, 1995)					
	11_a Human work (sej/hour)	2,97E+13	(this study; Slovenia 2002)					
	12_a Services (sej/USD)	5,99E+12	(this study; Slovenia 2002)					
Y1	**Annual flows**							
	13 Aboveground wood/y (sej/J)	1,96E+04	1,11E+04	8,56E+03	1,23E+04	9,03E+03	1,17E+04	7,38E+03
	13_a Aboveground wood/$_{4\text{-}10}$ (sej/J)	1,71E+04	7,36E+03	7,24E+03	9,04E+03	6,77E+03	9,09E+03	5,56E+03
	$13_{/w}$ Aboveground wood/y (sej/J)	1,13E+04	1,08E+04	8,28E+03	1,20E+04	8,30E+03	1,14E+04	6,74E+03
	$13a_{/w}$ Aboveground wood/$_{4\text{-}10}$ (sej/J)	8,82E+03	7,04E+03	6,95E+03	8,76E+03	6,04E+03	8,79E+03	4,93E+03
	14 Leaves/y (sej/g)	3,53E+08	2,01E+08	1,55E+08	2,22E+08	1,63E+08	2,11E+08	1,33E+08
	15 NPP/y (sej/J)	4,32E+03	2,46E+03	1,89E+03	2,71E+03	1,99E+03	2,58E+03	1,63E+03
	16 Aboveground biomass/y (sej/J)	6,93E+03	3,94E+03	3,03E+03	4,35E+03	3,20E+03	4,14E+03	2,61E+03
	$16_{/w}$ Aboveground biomass/y (sej/J)	3,99E+03	3,83E+03	2,93E+03	4,25E+03	2,94E+03	4,03E+03	2,39E+03
	17_a N_2 fixed/y (g/ha/y)	8,12E+04	4,62E+04	3,55E+04	5,10E+04	3,75E+04	4,85E+04	3,06E+04
	17_b N in the parent material/y (sej/g)	2,41E+09			(Brandt-Williams, 2002)			
	17_c N mineralized/y (g/ha/y)	5,58E+08	5,13E+08	5,13E+08	5,12E+08	5,11E+08	5,08E+08	5,09E+08
	18 Run out/y (sej/J)	6,80E+04	7,26E+04	7,69E+04	5,72E+04	6,40E+04	6,21E+04	7,00E+04
	18_a Run out/$y_{4\text{-}10(minL)}$ (sej/J)	5,63E+04	8,62E+04	2,75E+06	3,17E+04	3,57E+04	3,07E+04	5,41E+04
	18_b Run out/$y_{4\text{-}10(averL)}$ (sej/J)	4,78E+04	2,46E+05	9,86E+04	3,47E+04	3,16E+04	3,16E+04	5,61E+04
	18_c Run out/$y_{4\text{-}10(calc\ const)}$ (sej/J)	1,19E+05	1,19E+05	1,19E+05	1,19E+05	1,19E+05	1,19E+05	1,19E+05
Q1	**Stored quantities**							
	19 Water at stand (sej/J)	7,36E+04	7,26E+04	7,69E+04	5,72E+04	6,40E+04	6,21E+04	7,00E+04
	19_a Water at $stand_{4\text{-}10(minL)}$ (sej/J)	7,73E+04	7,80E+04	7,89E+04	5,85E+04	6,50E+04	6,09E+04	7,27E+04
	19_b Water at $stand_{4\text{-}10(averL)}$ (sej/J)	7,79E+04	7,85E+04	7,95E+04	6,03E+04	6,59E+04	6,24E+04	7,34E+04
	20 Standing wood (sej/J)	1,96E+04	1,94E+04	1,91E+04	1,89E+04	1,87E+04	1,85E+04	1,83E+04
	20_a Standing wood/$_{4\text{-}10}$ (sej/J)	1,92E+05	1,88E+05	1,83E+05	1,79E+05	1,74E+05	1,71E+05	1,67E+05
	$20_{/w}$ Standing wood/y (sej/J)	1,13E+04	1,13E+04	1,12E+04	1,12E+04	1,11E+04	1,11E+04	1,10E+04
	21 Total standing biomass (sej/J)	2,64E+04	2,54E+04	2,44E+04	2,36E+04	2,27E+04	2,21E+04	2,14E+04
	22 Organic matter in the soil (sej/J)	2,32E+02	8,01E+03	8,09E+03	8,22E+03	8,33E+03	8,44E+03	8,53E+03
Y2	**Final products**							
	23 Removed wood/y (sej/J)	2,60E+04				2,81E+04		2,76E+04
	23_a Removed wood/$_{4\text{-}10}$ (sej/J)	1,98E+05				1,84E+05		1,76E+05

Table F2– continued 1

Note	Item	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
I											
N	5	5,05E+08	5,04E+08	5,03E+08	5,01E+08	5,01E+08	5,01E+08	4,98E+08	4,97E+08	4,97E+08	4,94E+08
Y1											
	13	1,19E+04	1,12E+04	1,18E+04	1,46E+04	1,24E+04	9,59E+03	1,68E+04	1,42E+04	1,12E+04	1,73E+04
	13_{a}	8,03E+03	7,32E+03	8,12E+03	9,95E+03	8,89E+03	6,32E+03	1,35E+04	1,16E+04	8,05E+03	1,24E+04
	$13_{/w}$	1,16E+04	1,09E+04	1,14E+04	1,38E+04	1,16E+04	9,29E+03	1,58E+04	1,38E+04	1,08E+04	1,68E+04
	$13_{/w}$	7,68E+03	7,00E+03	7,77E+03	9,14E+03	8,12E+03	6,02E+03	1,25E+04	1,12E+04	7,70E+03	1,19E+04
	14	2,15E+08	2,03E+08	2,12E+08	2,63E+08	2,24E+08	1,73E+08	3,03E+08	2,46E+08	2,01E+08	3,12E+08
	15	2,63E+03	2,48E+03	2,60E+03	3,22E+03	2,74E+03	2,12E+03	3,70E+03	3,00E+03	2,46E+03	3,81E+03
	16	4,22E+03	3,98E+03	4,16E+03	5,16E+03	4,39E+03	3,40E+03	5,94E+03	4,82E+03	3,95E+03	6,11E+03
	$16_{/w}$	4,10E+03	3,87E+03	4,04E+03	4,87E+03	4,12E+03	3,29E+03	5,58E+03	4,89E+03	3,83E+03	5,94E+03
	17_{a}	4,95E+04	4,67E+04	4,88E+04	6,05E+04	5,15E+04	3,98E+04	6,96E+04	5,65E+04	4,63E+04	7,16E+04
	17_{c}	5,05E+08	5,04E+08	5,03E+08	5,01E+08	5,01E+08	5,01E+08	4,98E+08	4,97E+08	4,97E+08	4,94E+08
	18	6,89E+04	7,90E+04	7,42E+04	6,82E+04	6,50E+04	7,35E+04	6,45E+04	7,44E+04	7,05E+04	6,98E+04
	18_{a}	4,79E+04	0	5,70E+04	6,68E+04	4,53E+04	7,55E+04	3,50E+04	0	7,22E+04	1,04E+05
	18_{b}	5,07E+04	5,66E+06	7,25E+04	6,30E+04	5,59E+04	5,12E+04	3,81E+04	0	8,71E+04	8,27E+04
	18_{c}	1,19E+05	1,19E+05	1,19E+05	1,19E+05	1,19E+05	1,19E+05	1,19E+05	1,19E+05	1,19E+05	1,19E+05
Q1											
	19	6,89E+04	7,90E+04	7,42E+04	6,82E+04	6,50E+04	7,35E+04	6,45E+04	7,44E+04	7,05E+04	6,98E+04
	19_{a}	7,22E+04	8,22E+04	7,56E+04	7,81E+04	6,93E+04	7,39E+04	6,69E+04	7,93E+04	7,66E+04	8,02E+04
	19_{b}	7,29E+04	8,26E+04	7,62E+04	7,86E+04	7,02E+04	7,46E+04	6,82E+04	7,98E+04	7,71E+04	8,06E+04
	20	1,81E+04	1,80E+04	1,79E+04	1,78E+04	1,77E+04	1,76E+04	1,76E+04	1,75E+04	1,74E+04	1,74E+04
	20_{a}	1,64E+05	1,61E+05	1,58E+05	1,56E+05	1,53E+05	1,51E+05	1,49E+05	1,47E+05	1,45E+05	1,43E+05
	$20_{/w}$	1,10E+04	1,10E+04	1,10E+04	1,11E+04	1,11E+04	1,10E+04	1,11E+04	1,11E+04	1,11E+04	1,12E+04
	21	2,09E+04	2,04E+04	2,00E+04	2,15E+04	2,18E+04	2,12E+04	2,13E+04	2,10E+04	2,05E+04	2,03E+04
	22	8,63E+03	8,73E+03	8,83E+03	8,93E+03	9,04E+03	9,13E+03	9,25E+03	9,36E+03	9,45E+03	9,55E+03
Y2											
	23				2,70E+04	2,71E+04		2,69E+04			
	23_{a}				1,65E+05	1,63E+05		1,58E+05			

Table F2 – continued 2

Note	Item	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
I											
N	5	4,95E+08	4,94E+08	4,93E+08	4,93E+08	4,91E+08	4,91E+08	4,89E+08	4,90E+08	4,89E+08	4,87E+08
Y1											
	13	1,24E+04	1,36E+04	1,44E+04	1,07E+04	1,44E+04	1,22E+04	1,39E+04	9,00E+03	1,00E+04	1,16E+04
	13_a	9,22E+03	9,72E+03	1,01E+04	7,88E+03	1,13E+04	8,92E+03	1,09E+04	7,02E+03	7,28E+03	8,33E+03
	$13_{/w}$	1,15E+04	1,28E+04	1,40E+04	9,94E+03	1,40E+04	1,15E+04	1,35E+04	8,72E+03	9,77E+03	1,08E+04
	$13_{/w}$	8,34E+03	8,85E+03	9,74E+03	7,13E+03	1,09E+04	8,18E+03	1,05E+04	6,74E+03	7,01E+03	7,56E+03
	14	2,24E+08	2,46E+08	2,61E+08	1,93E+08	2,59E+08	2,21E+08	2,51E+08	1,62E+08	1,81E+08	2,10E+08
	15	2,74E+03	3,01E+03	3,19E+03	2,36E+03	3,17E+03	2,70E+03	3,07E+03	1,99E+03	2,22E+03	2,57E+03
	16	4,39E+03	4,82E+03	5,11E+03	3,79E+03	5,09E+03	4,33E+03	4,93E+03	3,19E+03	3,56E+03	4,11E+03
	$16_{/w}$	4,08E+03	4,52E+03	4,97E+03	3,52E+03	4,94E+03	4,07E+03	4,79E+03	3,09E+03	3,46E+03	3,84E+03
	17_a	5,15E+04	5,66E+04	5,99E+04	4,44E+04	5,96E+04	5,08E+04	5,78E+04	3,74E+04	4,17E+04	4,82E+04
	17_c	4,95E+08	4,94E+08	4,93E+08	4,93E+08	4,91E+08	4,91E+08	4,89E+08	4,90E+08	4,89E+08	4,87E+08
	18	7,10E+04	6,40E+04	7,53E+04	7,40E+04	7,36E+04	6,82E+04	7,83E+04	6,49E+04	7,07E+04	6,95E+04
	18_a	1,15E+05	3,85E+04	4,61E+05	3,34E+04	1,14E+05	5,81E+04	4,50E+05	5,70E+04	4,22E+04	8,56E+04
	18_b	8,23E+04	5,49E+04	9,44E+04	4,63E+04	7,26E+04	4,34E+04	0	5,34E+04	4,60E+04	6,10E+04
	18_c	1,19E+05	1,19E+05	1,19E+05	1,19E+05	1,19E+05	1,19E+05	1,19E+05	1,19E+05	1,19E+05	1,19E+05
Q1											
	19	7,10E+04	6,40E+04	7,53E+04	7,40E+04	7,36E+04	6,82E+04	7,83E+04	6,49E+04	7,07E+04	6,95E+04
	19_a	7,85E+04	7,07E+04	7,74E+04	7,00E+04	8,19E+04	7,45E+04	8,12E+04	7,22E+04	6,68E+04	7,80E+04
	19_b	7,90E+04	7,16E+04	7,79E+04	7,12E+04	8,23E+04	7,53E+04	8,14E+04	7,29E+04	6,79E+04	7,85E+04
	20	1,73E+04	1,73E+04	1,73E+04	1,71E+04	1,71E+04	1,70E+04	1,70E+04	1,68E+04	1,67E+04	1,67E+04
	20_a	1,41E+05	1,39E+05	1,38E+05	1,36E+05	1,34E+05	1,32E+05	1,31E+05	1,29E+05	1,27E+05	1,25E+05
	$20_{/w}$	1,12E+04	1,12E+04	1,12E+04	1,12E+04	1,13E+04	1,12E+04	1,13E+04	1,12E+04	1,12E+04	1,12E+04
	21	2,02E+04	2,00E+04	1,97E+04	1,94E+04	1,92E+04	2,05E+04	2,02E+04	1,98E+04	1,93E+04	1,92E+04
	22	9,65E+03	9,76E+03	9,87E+03	9,97E+03	1,01E+04	1,02E+04	1,03E+04	1,04E+04	1,05E+04	1,06E+04
Y2											
	23	2,66E+04	2,66E+04		2,64E+04		2,61E+04				2,59E+04
	23_a	1,51E+05	1,49E+05		1,45E+05		1,41E+05				1,34E+05

Table F2 – continued 3

Note	Item	1996	1997	1998	1999	2000	2001	2002	2003	2004
I										
N	*5*	*4,95E+08*	*4,94E+08*	*4,93E+08*	*4,93E+08*	*4,91E+08*	*4,91E+08*	*4,89E+08*	*4,90E+08*	*4,89E+08*
Y1										
	13	*1,50E+04*	*1,72E+04*	*1,29E+04*	*1,16E+04*	*1,76E+04*	*1,22E+04*	*2,00E+04*	*1,87E+04*	*2,09E+04*
	13_a	*1,15E+04*	*1,25E+04*	*1,05E+04*	*9,06E+03*	*1,08E+04*	*9,50E+03*	*1,34E+04*	*1,30E+04*	*1,75E+04*
	$13_{/w}$	*1,46E+04*	*1,67E+04*	*1,25E+04*	*1,13E+04*	*1,73E+04*	*1,19E+04*	*1,96E+04*	*1,84E+04*	*1,97E+04*
	$13_{/w}$	*1,11E+04*	*1,20E+04*	*1,01E+04*	*8,72E+03*	*1,04E+04*	*9,18E+03*	*1,31E+04*	*1,27E+04*	*1,63E+04*
	14	*2,71E+08*	*3,10E+08*	*2,32E+08*	*2,10E+08*	*2,48E+08*	*2,20E+08*	*3,01E+08*	*2,38E+08*	*3,77E+08*
	15	*3,31E+03*	*3,79E+03*	*2,84E+03*	*2,56E+03*	*3,03E+03*	*2,70E+03*	*3,68E+03*	*2,92E+03*	*4,61E+03*
	16	*5,31E+03*	*6,08E+03*	*4,56E+03*	*4,11E+03*	*4,86E+03*	*4,32E+03*	*5,90E+03*	*4,68E+03*	*7,39E+03*
	$16_{/w}$	*5,18E+03*	*5,91E+03*	*4,43E+03*	*3,99E+03*	*6,12E+03*	*4,21E+03*	*6,94E+03*	*6,53E+03*	*6,97E+03*
	17_a	*6,23E+04*	*7,13E+04*	*5,34E+04*	*4,82E+04*	*5,69E+04*	*5,07E+04*	*6,91E+04*	*5,48E+04*	*8,66E+04*
	17_c	*4,85E+08*	*4,83E+08*	*4,83E+08*	*4,83E+08*	*4,82E+08*	*4,81E+08*	*4,80E+08*	*4,80E+08*	*4,75E+08*
	18	*6,09E+04*	*7,82E+04*	*6,99E+04*	*7,55E+04*	*7,75E+04*	*8,10E+04*	*7,99E+04*	*7,77E+04*	*6,83E+04*
	18_a	*3,86E+04*	*0*	*3,73E+04*	*0*	*0*	*4,14E+05*	*0*	*5,69E+03*	*7,00E+04*
	18_b	*4,45E+04*	*2,59E+05*	*3,83E+04*	*0*	*0*	*1,41E+05*	*0*	*5,41E+03*	*7,00E+04*
	18_c	*1,19E+05*	*1,19E+05*	*1,19E+05*	*1,19E+05*	*1,19E+05*	*1,19E+05*	*1,19E+05*	*1,19E+05*	*1,19E+05*
Q1										
	19	*6,09E+04*	*7,82E+04*	*6,99E+04*	*7,55E+04*	*7,75E+04*	*8,10E+04*	*7,99E+04*	*7,77E+04*	*6,83E+04*
	19_a	*6,81E+04*	*8,29E+04*	*6,94E+04*	*8,32E+04*	*8,04E+04*	*7,76E+04*	*8,10E+04*	*7,82E+04*	*7,64E+04*
	19_b	*6,92E+04*	*8,33E+04*	*7,05E+04*	*8,35E+04*	*8,09E+04*	*7,82E+04*	*8,13E+04*	*7,87E+04*	*7,70E+04*
	20	*1,66E+04*	*1,66E+04*	*1,66E+04*	*1,65E+04*	*1,65E+04*	*1,65E+04*	*1,65E+04*	*1,66E+04*	*1,66E+04*
	20_a	*1,23E+05*	*1,22E+05*	*1,21E+05*	*1,20E+05*	*1,18E+05*	*1,17E+05*	*1,16E+05*	*1,14E+05*	*1,13E+05*
	$20_{/w}$	*1,12E+04*	*1,13E+04*	*1,13E+04*	*1,13E+04*	*1,14E+04*	*1,14E+04*	*1,15E+04*	*1,16E+04*	*1,16E+04*
	21	*1,90E+04*	*1,88E+04*	*1,86E+04*	*1,83E+04*	*1,82E+04*	*1,79E+04*	*1,78E+04*	*1,77E+04*	*1,76E+04*
	22	*1,07E+04*	*1,08E+04*	*1,09E+04*	*1,10E+04*	*1,12E+04*	*1,13E+04*	*1,14E+04*	*1,16E+04*	*1,17E+04*
Y2										
	23									*2,56E+04*
	23_a									*1,22E+05*

APPENDIX F3: Emergy evaluation table: Emergy of flows and storages

***Table F3** Emergy evaluation table: emergy of annual flows for 35 years under study. Emergy flows were calculated by multiplying flows in physical units by corresponding UEVs.*
(Precipitation: chemical potential emergy; >ET/prec (or >): higher among adapted potential evapotranspiration and precipitation; for other abbreviations see Tables F1 and F2)

Note	Item	<1970	1970	1971	1972	1973	1974	1975
I	**Environmental sources (sej/ha/y)**							
R	1 ET_{oa}	2,59E+16	7,79E+14	6,60E+14	7,73E+14	6,33E+14	7,09E+14	6,28E+14
	1_a ET_{oa4-10}	1,80E+16	5,14E+14	4,82E+14	4,79E+14	3,90E+14	4,22E+14	4,50E+14
	2 Precipitation	2,35E+16	6,96E+14	5,04E+14	1,01E+15	7,39E+14	8,51E+14	6,15E+14
	2_a $Precipitation_{4-10}$	1,62E+16	4,24E+14	2,91E+14	7,50E+14	5,50E+14	6,53E+14	4,66E+14
	> ET/prec	2,59E+16	7,79E+14	6,60E+14	1,01E+15	7,39E+14	8,51E+14	6,28E+14
	> $ET/prec_{4-10}$	1,80E+16	5,14E+14	4,82E+14	7,50E+14	5,50E+14	6,53E+14	4,66E+14
	3 Run-in of gw	0	0	0	0	0	0	0
	3_a Run-in of gw_{4-10}	0	0	9,24E+13	0	0	0	0
	4 White frost	0	0	0	0	0	0	0
N	5 Leached N	3,05E+15	9,20E+13	7,63E+13	8,41E+13	8,60E+13	9,33E+13	7,79E+13
F1	**Purchased sources (sej/ha/y)**							
	6 Plantings	1,05E+16	0	0	0	0	0	0
	7 Wood for roads	1,51E+14	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12
	8 Gravel for roads	6,37E+14	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13
	9_a Machinery-standing	1,65E+14	1,12E+11	1,12E+11	1,12E+11	1,17E+11	1,12E+11	1,17E+11
	10_a Petrol-standing	7,98E+14	3,15E+11	3,15E+11	3,15E+11	6,56E+11	3,15E+11	6,16E+11
	11_a Human work-standing	1,06E+16	4,96E+11	4,96E+11	4,96E+11	2,00E+13	4,96E+11	1,77E+13
	12_a Services-standing	1,68E+16	1,71E+12	1,71E+12	1,71E+12	2,89E+13	1,71E+12	2,57E+13
	Purchased sources - final harvest (sej/ha/y)							
	9_b Machinery-removed	5,55E+13	0	0	0	1,95E+11	0	4,22E+11
	10_b Petrol-removed	2,93E+14	0	0	0	1,03E+12	0	2,24E+12
	11_b Human work-removed	4,64E+15	0	0	0	1,50E+13	0	3,30E+13
	12_b Services-removed	7,17E+15	0	0	0	2,35E+13	0	5,15E+13
Y1	**Outputs - annual flows (sej/ha/y)**							
	13 Aboveground-wood/y	6,86E+16	8,96E+14	7,62E+14	1,12E+15	8,97E+14	9,69E+14	7,73E+14
	13_a Aboveground-wood/$_{4-10}$	6,00E+16	5,93E+14	6,44E+14	8,24E+14	6,73E+14	7,53E+14	5,83E+14
	$13_{/w}$ Aboveground-wood/y	3,95E+16	8,71E+14	7,37E+14	1,09E+15	8,25E+14	9,44E+14	7,06E+14
	$13_{a/w}$ Aboveground-wood/$_{4-10}$	3,09E+16	5,68E+14	6,19E+14	7,99E+14	6,01E+14	7,28E+14	5,16E+14
	14 Leaves	6,86E+16	8,96E+14	7,62E+14	1,12E+15	8,97E+14	9,69E+14	7,73E+14
	15 NPP	6,86E+16	8,96E+14	7,62E+14	1,12E+15	8,97E+14	9,69E+14	7,73E+14
	16 Aboveground biomass/y	6,86E+16	8,96E+14	7,62E+14	1,12E+15	8,97E+14	9,69E+14	7,73E+14
	$16_{/w}$ Aboveground biomass/y	3,95E+16	8,71E+14	7,37E+14	1,09E+15	8,25E+14	9,44E+14	7,06E+14
	17_a N_2 fixed	6,73E+11	8,78E+09	7,47E+09	1,10E+10	8,79E+09	9,50E+09	7,57E+09
	17_b N from the soil	1,98E+15	4,19E+13	4,62E+13	4,72E+13	5,14E+13	4,26E+13	5,40E+13
	18 Run out	2,35E+16	9,95E+14	1,64E+14	1,75E+15	1,02E+15	1,40E+15	7,53E+14
	18_a Run $out_{4-10(minL)}$	1,62E+16	4,24E+14	2,91E+14	7,50E+14	5,50E+14	6,53E+14	4,66E+14
	18_b Run $out_{4-10(averL)}$	1,62E+16	4,24E+14	2,91E+14	7,50E+14	5,50E+14	6,53E+14	4,66E+14
	18_c Run $out_{4-10(calc\ const)}$	1,62E+16	4,24E+14	2,91E+14	7,50E+14	5,50E+14	6,53E+14	4,66E+14
Q1	**Stored quantities (sej/ha)**							
	19 Water in the stand	4,73E+15	4,70E+15	4,73E+15	3,63E+15	3,88E+15	3,89E+15	4,30E+15
	19_a Water in the stand/$_{4-10(minL)}$	4,68E+15	4,71E+15	4,67E+15	3,46E+15	3,76E+15	3,55E+15	4,30E+15
	19_b Water in the stand/$_{4-10(averL)}$	5,00E+15	5,00E+15	4,84E+15	3,87E+15	3,95E+15	3,90E+15	4,50E+15
	20 Standing wood	3,16E+16	3,29E+16	3,42E+16	3,56E+16	3,69E+16	3,81E+16	3,93E+16
	20_a Standing $wood_{4-10}$	3,10E+17	3,19E+17	3,27E+17	3,36E+17	3,44E+17	3,52E+17	3,59E+17
	$20_{/w}$ Standing wood	1,82E+16	1,91E+16	2,00E+16	2,10E+16	2,20E+16	2,29E+16	2,37E+16
	21 Total standing biomass	6,86E+16	6,95E+16	7,03E+16	7,14E+16	7,23E+16	7,33E+16	7,41E+16
	22 Organic matter in the soil	6,86E+16	6,95E+16	7,03E+16	7,14E+16	7,23E+16	7,33E+16	7,41E+16
Y2	**Final products (sej/ha)**							
	23 Removed wood	4,91E+16				1,19E+14		2,57E+14
	23_a Removed $wood_{4-10}$	3,75E+17				7,76E+14		1,64E+15

Table F3 – continued 1

Note	Item	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
I											
R	1	7,12E+14	7,94E+14	6,75E+14	7,70E+14	7,27E+14	7,04E+14	7,54E+14	8,05E+14	7,33E+14	7,52E+14
	1_a	4,61E+14	4,71E+14	4,50E+14	5,27E+14	4,97E+14	4,47E+14	5,20E+14	5,98E+14	5,30E+14	5,48E+14
	2	7,12E+14	5,74E+14	5,72E+14	7,79E+14	8,11E+14	6,10E+14	8,46E+14	5,12E+14	6,99E+14	7,33E+14
	2_a	4,83E+14	3,09E+14	4,14E+14	4,33E+14	5,73E+14	4,41E+14	6,36E+14	3,59E+14	4,64E+14	4,12E+14
	$>$	7,12E+14	7,94E+14	6,75E+14	7,79E+14	8,11E+14	7,04E+14	8,46E+14	8,05E+14	7,33E+14	7,52E+14
	$>_{4-10}$	4,83E+14	4,71E+14	4,50E+14	5,27E+14	5,73E+14	4,47E+14	6,36E+14	5,98E+14	5,30E+14	5,48E+14
	3	0	0	0	0	0	0	0	3,37E+13	0	0
	3_a	0	4,23E+13	0	0	0	0	0	1,02E+14	0	0
	4	3,01E+13	0	5,87E+13	5,42E+13	0	0	2,49E+13	0	0	4,26E+13
N	5	9,77E+13	6,76E+13	7,32E+13	6,55E+13	6,04E+13	6,92E+13	7,65E+13	5,52E+13	5,98E+13	6,69E+13
F1											
	6	0	0	0	0	0	0	0	0	0	0
	7	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12
	8	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13
	9_a	1,12E+11	1,12E+11	1,12E+11	1,15E+11	1,15E+11	1,12E+11	1,16E+11	1,12E+11	1,12E+11	1,12E+11
	10_a	3,15E+11	3,15E+11	3,15E+11	5,15E+11	5,47E+11	3,15E+11	5,71E+11	3,15E+11	3,15E+11	3,15E+11
	11_a	4,96E+11	4,96E+11	4,96E+11	1,19E+13	1,37E+13	4,96E+11	1,51E+13	4,96E+11	4,96E+11	4,96E+11
	12_a	1,71E+12	1,71E+12	1,71E+12	1,77E+13	2,02E+13	1,71E+12	2,21E+13	1,71E+12	1,71E+12	1,71E+12
	9_b	0	0	0	8,09E+12	3,70E+12	0	1,81E+12	0	0	0
	10_b	0	0	0	4,40E+13	1,97E+13	0	9,68E+12	0	0	0
	11_b	0	0	0	7,00E+14	2,96E+14	0	1,46E+14	0	0	0
	12_b	0	0	0	1,08E+15	4,61E+14	0	2,27E+14	0	0	0
Y1											
	13	8,65E+14	8,87E+14	8,32E+14	9,52E+14	9,29E+14	7,98E+14	1,01E+15	9,25E+14	8,18E+14	8,87E+14
	13_a	5,83E+14	5,77E+14	5,75E+14	6,50E+14	6,65E+14	5,26E+14	8,11E+14	7,56E+14	5,90E+14	6,37E+14
	$13_{/w}$	8,40E+14	8,62E+14	8,07E+14	8,99E+14	8,71E+14	7,73E+14	9,47E+14	8,99E+14	7,93E+14	8,62E+14
	$13_{a/w}$	5,58E+14	5,52E+14	5,50E+14	5,97E+14	6,08E+14	5,01E+14	7,51E+14	7,31E+14	5,65E+14	6,12E+14
	14	8,65E+14	8,87E+14	8,32E+14	9,52E+14	9,29E+14	7,98E+14	1,01E+15	8,85E+14	8,18E+14	8,87E+14
	15	8,65E+14	8,87E+14	8,32E+14	9,52E+14	9,29E+14	7,98E+14	1,01E+15	8,85E+14	8,18E+14	8,87E+14
	16	8,65E+14	8,87E+14	8,32E+14	9,52E+14	9,29E+14	7,98E+14	1,01E+15	8,85E+14	8,18E+14	8,87E+14
	$16_{/w}$	8,40E+14	8,62E+14	8,07E+14	8,99E+14	8,71E+14	7,73E+14	9,47E+14	8,99E+14	7,93E+14	8,62E+14
	17_a	8,48E+09	8,69E+09	8,15E+09	9,33E+09	9,10E+09	7,82E+09	9,88E+09	8,68E+09	8,02E+09	8,70E+09
	17_b	3,71E+13	4,03E+13	3,60E+13	3,31E+13	3,80E+13	4,22E+13	3,03E+13	3,28E+13	3,69E+13	2,57E+13
	18	8,46E+14	3,09E+14	4,52E+14	1,01E+15	1,36E+15	3,72E+14	1,30E+15	0	8,09E+14	8,60E+14
	18_a	4,83E+14	0	4,14E+14	4,33E+14	5,73E+14	4,41E+14	6,36E+14	0	4,64E+14	4,12E+14
	18_b	4,83E+14	3,09E+14	4,14E+14	4,33E+14	5,73E+14	4,41E+14	6,36E+14	0	4,64E+14	4,12E+14
	18_c	4,83E+14	3,09E+14	4,14E+14	4,33E+14	5,73E+14	4,41E+14	6,36E+14	3,59E+14	4,64E+14	4,12E+14
Q1											
	19	4,28E+15	5,01E+15	4,65E+15	4,36E+15	4,18E+15	4,55E+15	4,21E+15	4,81E+15	4,56E+15	4,56E+15
	19_a	4,24E+15	4,90E+15	4,51E+15	4,79E+15	4,20E+15	4,38E+15	4,03E+15	4,97E+15	4,66E+15	4,92E+15
	19_b	4,48E+15	5,17E+15	4,82E+15	4,98E+15	4,51E+15	4,66E+15	4,49E+15	5,23E+15	5,02E+15	5,23E+15
	20	4,04E+16	4,15E+16	4,25E+16	4,00E+16	3,97E+16	4,08E+16	4,11E+16	4,22E+16	4,32E+16	4,41E+16
	20_a	3,65E+17	3,71E+17	3,76E+17	3,50E+17	3,43E+17	3,50E+17	3,49E+17	3,54E+17	3,59E+17	3,63E+17
	$20_{/w}$	2,45E+16	2,54E+16	2,62E+16	2,48E+16	2,48E+16	2,56E+16	2,60E+16	2,68E+16	2,76E+16	2,83E+16
	21	7,49E+16	7,58E+16	7,66E+16	7,76E+16	7,85E+16	7,93E+16	8,03E+16	8,12E+16	8,21E+16	8,30E+16
	22	7,49E+16	7,58E+16	7,66E+16	7,76E+16	7,85E+16	7,93E+16	8,03E+16	8,12E+16	8,21E+16	8,30E+16
Y2											
	23				5,42E+15	2,26E+15		1,11E+15			
	23_a				3,32E+16	1,36E+16		6,54E+15			

Table F3 – continued 2

Note	Item	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
I											
R	1	7,55E+14	7,35E+14	7,75E+14	7,55E+14	7,94E+14	7,49E+14	8,20E+14	6,36E+14	8,06E+14	7,73E+14
	1_a	5,53E+14	5,12E+14	5,09E+14	4,90E+14	6,37E+14	5,31E+14	5,33E+14	4,39E+14	4,58E+14	5,48E+14
	2	7,09E+14	8,38E+14	6,36E+14	6,45E+14	6,87E+14	7,66E+14	6,12E+14	7,24E+14	7,58E+14	7,57E+14
	2_a	4,47E+14	5,58E+14	4,31E+14	5,49E+14	4,50E+14	5,03E+14	3,84E+14	4,64E+14	5,82E+14	4,52E+14
	$>$	7,55E+14	8,38E+14	7,75E+14	7,55E+14	7,94E+14	7,66E+14	8,20E+14	7,24E+14	8,06E+14	7,73E+14
	$>_{4-10}$	5,53E+14	5,58E+14	5,09E+14	5,49E+14	6,37E+14	5,31E+14	5,33E+14	4,64E+14	5,82E+14	5,48E+14
	3	0	0	0	0	0	0	0	0	0	0
	3_a	0	0	0	0	0	0	3,93E+13	1,93E+12	0	0
	4	0	0	8,16E+13	0	0	0	0	0	0	0
N	5	4,70E+13	6,35E+13	6,43E+13	5,97E+13	7,42E+13	5,63E+13	6,46E+13	5,92E+13	8,12E+13	8,17E+13
F1											
	6	0	0	0	0	0	0	0	0	0	0
	7	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12
	8	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13
	9_a	1,16E+11	1,16E+11	1,12E+11	1,16E+11	1,12E+11	1,15E+11	1,12E+11	1,12E+11	1,12E+11	1,16E+11
	10_a	5,78E+11	5,78E+11	3,15E+11	5,82E+11	3,15E+11	5,15E+11	3,15E+11	3,15E+11	3,15E+11	5,74E+11
	11_a	1,55E+13	1,55E+13	4,96E+11	1,57E+13	4,96E+11	1,19E+13	4,96E+11	4,96E+11	4,96E+11	1,53E+13
	12_a	2,27E+13	2,27E+13	1,71E+12	2,30E+13	1,71E+12	1,76E+13	1,71E+12	1,71E+12	1,71E+12	2,23E+13
	9_b	8,58E+11	8,55E+11	0	6,68E+11	0	8,93E+12	0	0	0	1,21E+12
	10_b	4,59E+12	4,58E+12	0	3,58E+12	0	4,90E+13	0	0	0	6,49E+12
	11_b	6,99E+13	6,99E+13	0	5,50E+13	0	8,02E+14	0	0	0	1,01E+14
	12_b	1,09E+14	1,09E+14	0	8,54E+13	0	1,24E+15	0	0	0	1,56E+14
Y1											
	13	8,63E+14	9,63E+14	9,46E+14	8,76E+14	8,94E+14	8,75E+14	9,10E+14	8,09E+14	9,13E+14	9,16E+14
	13_a	6,42E+14	6,87E+14	6,64E+14	6,46E+14	7,05E+14	6,38E+14	7,13E+14	6,31E+14	6,62E+14	6,56E+14
	$13_{/w}$	8,02E+14	9,02E+14	9,21E+14	8,14E+14	8,68E+14	8,22E+14	8,85E+14	7,84E+14	8,87E+14	8,55E+14
	$13_{a/w}$	5,81E+14	6,26E+14	6,39E+14	5,84E+14	6,80E+14	5,85E+14	6,88E+14	6,06E+14	6,37E+14	5,96E+14
	14	8,63E+14	9,63E+14	9,46E+14	8,76E+14	8,94E+14	8,75E+14	9,10E+14	8,09E+14	9,13E+14	9,16E+14
	15	8,63E+14	9,63E+14	9,46E+14	8,76E+14	8,94E+14	8,75E+14	9,10E+14	8,09E+14	9,13E+14	9,16E+14
	16	8,63E+14	9,63E+14	9,46E+14	8,76E+14	8,94E+14	8,75E+14	9,10E+14	8,09E+14	9,13E+14	9,16E+14
	$16_{/w}$	8,02E+14	9,02E+14	9,21E+14	8,14E+14	8,68E+14	8,22E+14	8,85E+14	7,84E+14	8,87E+14	8,55E+14
	17_a	8,46E+09	9,44E+09	9,27E+09	8,59E+09	8,76E+09	8,58E+09	8,92E+09	7,93E+09	8,94E+09	8,97E+09
	17_b	3,49E+13	3,54E+13	3,27E+13	4,09E+13	3,09E+13	3,55E+13	3,24E+13	4,46E+13	4,50E+13	3,88E+13
	18	9,91E+14	1,32E+15	5,55E+14	5,02E+14	5,88E+14	1,26E+15	5,40E+14	9,38E+14	7,67E+14	8,44E+14
	18_a	4,47E+14	5,58E+14	4,31E+14	5,49E+14	4,50E+14	5,03E+14	3,84E+14	4,64E+14	5,82E+14	4,52E+14
	18_b	4,47E+14	5,58E+14	4,31E+14	5,49E+14	4,50E+14	5,03E+14	0	4,64E+14	5,82E+14	4,52E+14
	18_c	4,47E+14	5,58E+14	4,31E+14	5,49E+14	4,50E+14	5,03E+14	3,84E+14	4,64E+14	5,82E+14	4,52E+14
Q1											
	19	4,72E+15	4,13E+15	4,79E+15	4,70E+15	4,80E+15	4,54E+15	4,96E+15	3,95E+15	4,48E+15	4,54E+15
	19_a	4,83E+15	4,28E+15	4,76E+15	4,16E+15	5,23E+15	4,48E+15	4,72E+15	4,20E+15	3,96E+15	4,76E+15
	19_b	5,23E+15	4,60E+15	4,96E+15	4,69E+15	5,49E+15	5,08E+15	5,15E+15	4,40E+15	4,30E+15	5,07E+15
	20	4,48E+16	4,55E+16	4,66E+16	4,74E+16	4,84E+16	4,55E+16	4,65E+16	4,77E+16	4,89E+16	4,95E+16
	20_a	3,65E+17	3,67E+17	3,72E+17	3,75E+17	3,79E+17	3,53E+17	3,58E+17	3,64E+17	3,70E+17	3,71E+17
	$20_{/w}$	2,89E+16	2,95E+16	3,04E+16	3,10E+16	3,18E+16	3,01E+16	3,09E+16	3,18E+16	3,27E+16	3,33E+16
	21	8,38E+16	8,48E+16	8,57E+16	8,66E+16	8,75E+16	8,84E+16	8,93E+16	9,01E+16	9,10E+16	9,19E+16
	22	8,38E+16	8,48E+16	8,57E+16	8,66E+16	8,75E+16	8,84E+16	8,93E+16	9,01E+16	9,10E+16	9,19E+16
Y2											
	23	5,28E+14	5,27E+14		4,12E+14		6,04E+15				7,43E+14
	23_a	2,99E+15	2,95E+15		2,26E+15		3,27E+16				3,85E+15

Table F3 – continued 3

Note	Item	1996	1997	1998	1999	2000	2001	2002	2003	2004	average 1970-04
I											
R	1	7,37E+14	7,85E+14	7,89E+14	7,84E+14	8,61E+14	8,21E+14	1,08E+15	8,69E+14	7,58E+14	7,63E+14
	1_a	5,91E+14	5,78E+14	5,34E+14	6,18E+14	5,90E+14	6,05E+14	8,24E+14	5,81E+14	6,23E+14	5,30E+14
	2	9,18E+14	5,80E+14	7,62E+14	6,36E+14	4,99E+14	5,52E+14	6,02E+14	5,01E+14	7,74E+14	6,92E+14
	2_a	6,80E+14	3,83E+14	6,03E+14	4,13E+14	3,39E+14	3,88E+14	4,82E+14	3,65E+14	5,47E+14	4,77E+14
	>	9,18E+14	7,85E+14	7,89E+14	7,84E+14	8,61E+14	8,21E+14	1,08E+15	8,69E+14	7,74E+14	7,93E+14
	$>_{4-10}$	6,80E+14	5,78E+14	6,03E+14	6,18E+14	5,90E+14	6,05E+14	8,24E+14	5,81E+14	6,23E+14	5,67E+14
	3	0	0	0	0	2,34E+14	0	2,06E+14	3,95E+14	0	2,48E+13
	3_a	0	0	0	0	9,73E+13	5,36E+13	6,75E+13	3,15E+14	0	2,32E+13
	4	0	4,42E+13	2,87E+13	0	0	6,62E+13	3,01E+13	1,38E+14	1,82E+13	1,76E+13
N	5	7,06E+13	6,03E+13	4,76E+13	6,17E+13	6,67E+13	6,18E+13	7,07E+13	6,42E+13	7,29E+13	6,94E+13
F1											
	6	0	0	0	0	0	0	0	0	0	0
	7	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12	4,43E+12
	8	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13	1,87E+13
	9_a	1,12E+11	1,12E+11	1,12E+11	1,12E+11	1,12E+11	1,12E+11	1,12E+11	1,12E+11	1,15E+11	1,13E+11
	10_a	3,15E+11	3,15E+11	3,15E+11	3,15E+11	3,15E+11	3,15E+11	3,15E+11	3,15E+11	5,14E+11	3,95E+11
	11_a	4,96E+11	4,96E+11	4,96E+11	4,96E+11	4,96E+11	4,96E+11	4,96E+11	4,96E+11	1,19E+13	5,03E+12
	12_a	1,71E+12	1,71E+12	1,71E+12	1,71E+12	1,71E+12	1,71E+12	1,71E+12	1,71E+12	1,76E+13	8,04E+12
	9_b	0	0	0	0	0	0	0	0	1,34E+14	4,60E+12
	10_b	0	0	0	0	0	0	0	0	7,42E+14	2,54E+13
	11_b	0	0	0	0	0	0	0	0	1,24E+16	4,19E+14
	12_b	0	0	0	0	0	0	0	0	1,90E+16	6,44E+14
Y1											
	13	1,01E+15	9,15E+14	8,90E+14	8,71E+14	1,22E+15	9,74E+14	1,45E+15	1,56E+15	9,18E+14	9,45E+14
	13_a	7,75E+14	6,64E+14	7,26E+14	6,79E+14	7,50E+14	7,58E+14	9,75E+14	1,08E+15	7,70E+14	6,93E+14
	$13_{/w}$	9,89E+14	8,90E+14	8,65E+14	8,46E+14	1,20E+15	9,49E+14	1,42E+15	1,53E+15	8,65E+14	9,09E+14
	$13_{a/w}$	7,50E+14	6,39E+14	7,01E+14	6,54E+14	7,25E+14	7,32E+14	9,50E+14	1,06E+15	7,17E+14	6,57E+14
	14	1,01E+15	9,15E+14	8,90E+14	8,71E+14	9,53E+14	9,74E+14	1,21E+15	1,10E+15	9,18E+14	9,17E+14
	15	1,01E+15	9,15E+14	8,90E+14	8,71E+14	9,53E+14	9,74E+14	1,21E+15	1,10E+15	9,18E+14	9,17E+14
	16	1,01E+15	9,15E+14	8,90E+14	8,71E+14	9,53E+14	9,74E+14	1,21E+15	1,10E+15	9,18E+14	9,17E+14
	$16_{/w}$	9,89E+14	8,90E+14	8,65E+14	8,46E+14	1,20E+15	9,49E+14	1,42E+15	1,53E+15	8,65E+14	9,09E+14
	17_a	9,94E+09	8,97E+09	8,73E+09	8,54E+09	9,34E+09	9,55E+09	1,18E+10	1,07E+10	9,00E+09	8,98E+09
	17_b	3,32E+13	2,60E+13	3,38E+13	3,67E+13	3,38E+13	3,89E+13	3,52E+13	4,03E+13	2,12E+13	3,73E+13
	18	1,57E+15	2,75E+14	9,78E+14	6,27E+14	0	4,29E+13	0	0	1,31E+15	7,58E+14
	18_a	6,80E+14	0	6,03E+14	0	0	3,88E+14	0	3,65E+14	5,47E+14	4,11E+14
	18_b	6,80E+14	3,83E+14	6,03E+14	0	0	3,88E+14	0	3,65E+14	5,47E+14	4,20E+14
	18_c	6,80E+14	3,83E+14	6,03E+14	4,13E+14	3,39E+14	3,88E+14	4,82E+14	3,65E+14	5,47E+14	4,77E+14
Q1											
	19	4,09E+15	5,12E+15	4,60E+15	4,95E+15	4,97E+15	5,28E+15	5,24E+15	4,97E+15	4,64E+15	4,57E+15
	19_a	4,28E+15	5,21E+15	4,27E+15	5,20E+15	4,86E+15	4,79E+15	5,02E+15	4,76E+15	4,95E+15	4,54E+15
	19_b	4,67E+15	5,44E+15	4,68E+15	5,45E+15	5,14E+15	5,09E+15	5,38E+15	4,97E+15	5,24E+15	4,85E+15
	20	5,06E+16	5,15E+16	5,25E+16	5,35E+16	5,47E+16	5,58E+16	5,72E+16	5,86E+16	5,95E+16	4,56E+16
	20_a	3,75E+17	3,78E+17	3,83E+17	3,87E+17	3,91E+17	3,95E+17	4,00E+17	4,04E+17	4,07E+17	3,66E+17
	$20_{/w}$	3,42E+16	3,49E+16	3,57E+16	3,66E+16	3,76E+16	3,85E+16	3,97E+16	4,10E+16	4,17E+16	2,97E+16
	21	9,29E+16	9,38E+16	9,47E+16	9,56E+16	9,68E+16	9,78E+16	9,93E+16	1,01E+17	1,02E+17	8,49E+16
	22	9,29E+16	9,38E+16	9,47E+16	9,56E+16	9,68E+16	9,78E+16	9,93E+16	1,01E+17	1,02E+17	8,49E+16
Y2											
	23									9,17E+16	
	23_a									4,39E+17	

APPENDIX F4: Emergy evaluation table: Emergy of storages and emergy of R, N, M, S, and Y.

Table F4 *Emergy evaluation table: emergy of storages in 35 years under study and emergy of R, N, M, S, and Y. Emergy flows were calculated by multiplying flows in physical units by corresponding UEVs. (For symbols and abbreviations see Tables F1 and F2).*

Item-Cumulative	***<1970***	***1970***	***1971***	***1972***	***1973***	***1974***	***1975***
$1/2_{cum35-04}$ >ET/$rain_{(1935-04)}$ (sej/ha)	8,82E+17	8,82E+17	8,83E+17	8,84E+17	8,85E+17	8,86E+17	8,86E+17
$1_a/2_{a\ cum35-04}$ >ET/$rain_{4-10(1935-04)}$ (sej/ha)	6,33E+17	6,33E+17	6,34E+17	6,35E+17	6,35E+17	6,36E+17	6,36E+17
$1/2_{cum70-04}$ >ET/$rain_{(1970-04)}$ (sej/ha)	2,59E+16	2,67E+16	2,74E+16	2,84E+16	2,91E+16	3,00E+16	3,06E+16
$1_a/2_{a\ cum70-04}$ >ET/$rain_{4-10\ (1970-04)}$ (sej/ha)	1,86E+16	1,91E+16	1,96E+16	2,04E+16	2,09E+16	2,16E+16	2,21E+16
3_{cum} Run in (sej/ha)	0	0	0	0	0	0	0
$3_{ab\ cum}$ Run in_{4-10} (sej/ha)	0	0	9,24E+13	9,24E+13	9,24E+13	9,24E+13	9,24E+13
4_{cum} WF (sej/ha)	0	0	0	0	0	0	0
5_{cum} N leached (sej/ha)	3,05E+15	3,14E+15	3,22E+15	3,30E+15	3,39E+15	3,48E+15	3,56E+15
6_{cum} Plantings (sej/ha)	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16
7_{cum} Wood for roads (sej/ha)	1,32E+14	1,36E+14	1,40E+14	1,44E+14	1,48E+14	1,51E+14	1,55E+14
8_{cum} Gravel for roads (sej/ha)	6,37E+14	6,56E+14	6,74E+14	6,93E+14	7,12E+14	7,31E+14	7,49E+14
$9_{a\ cum}$ Machinery-standing (sej/ha)	1,65E+14	1,65E+14	1,65E+14	1,66E+14	1,66E+14	1,66E+14	1,66E+14
$10_{a\ cum}$ Petrol-standing (sej/ha)	7,98E+14	7,98E+14	7,98E+14	7,98E+14	7,99E+14	7,99E+14	8,00E+14
$11_{a\ cum}$ Human work-standing (sej/ha)	1,06E+16	1,06E+16	1,06E+16	1,06E+16	1,06E+16	1,06E+16	1,06E+16
$12_{a\ cum}$ Services-standing (sej/ha)	1,68E+16	1,68E+16	1,68E+16	1,68E+16	1,68E+16	1,68E+16	1,69E+16
$9_{b\ cum}$ Machinery-removed (sej/ha)	5,55E+13	5,55E+13	5,55E+13	5,55E+13	5,57E+13	5,57E+13	5,61E+13
$10_{b\ cum}$ Petrol-removed (sej/ha)	2,93E+14	2,93E+14	2,93E+14	2,93E+14	2,94E+14	2,94E+14	2,97E+14
$11_{b\ cum}$ Human work-removed (sej/ha)	4,64E+15	4,64E+15	4,64E+15	4,64E+15	4,65E+15	4,65E+15	4,68E+15
$12_{b\ cum}$ Services-removed (sej/ha)	7,17E+15	7,17E+15	7,17E+15	7,17E+15	7,20E+15	7,20E+15	7,25E+15
$R_{(1935-04)}$ (sej/ha)	2,75E+16	2,83E+16	2,89E+16	2,99E+16	3,07E+16	3,15E+16	3,22E+16
$R_{4-10\ (1935-04)}$ (sej/ha)	6,34E+17	6,35E+17	6,36E+17	6,36E+17	6,37E+17	6,37E+17	6,38E+17
$R_{produced\ (1935-04)}$ (sej/ha)	2,70E+16	2,78E+16	2,85E+16	2,95E+16	3,02E+16	3,11E+16	3,17E+16
$R_{produced/4-10\ (1935-04)}$ (sej/ha)	6,34E+17	6,34E+17	6,35E+17	6,36E+17	6,36E+17	6,37E+17	6,37E+17
$R_{/y\ (1970-04)}$ (sej/ha)	2,75E+16	7,79E+14	6,61E+14	1,01E+15	7,43E+14	8,51E+14	6,33E+14
$R_{4-10/y\ (1970-04)}$ (sej/ha)	2,02E+16	5,14E+14	5,74E+14	7,50E+14	5,54E+14	6,74E+14	4,76E+14
$R_{produced/y\ (1970-04)}$ (sej/ha)	2,70E+16	7,79E+14	6,60E+14	1,01E+15	7,41E+14	8,51E+14	6,30E+14
$R_{produced/4-10/y\ (1970-04)}$ (sej/ha)	1,97E+16	5,14E+14	5,74E+14	7,50E+14	5,52E+14	6,74E+14	4,72E+14
N (sej/ha)	3,05E+15	3,14E+15	3,22E+15	3,30E+15	3,39E+15	3,48E+15	3,56E+15
$M_{produced}$ (sej/ha)	1,23E+16	1,23E+16	1,23E+16	1,23E+16	1,24E+16	1,24E+16	1,24E+16
$M_{removed}$ (sej/ha)	3,49E+14	3,49E+14	3,49E+14	3,49E+14	3,50E+14	3,50E+14	3,53E+14
$S_{produced}$ (sej/ha)	2,63E+16	2,63E+16	2,63E+16	2,63E+16	2,63E+16	2,63E+16	2,64E+16
$S_{removed}$ (sej/ha)	1,13E+16	1,13E+16	1,13E+16	1,13E+16	1,14E+16	1,14E+16	1,15E+16
$Y_{1a\ produced\ wood/y}$ (sej/ha/y)	6,17E+16	8,96E+14	7,62E+14	1,12E+15	8,87E+14	9,69E+14	7,64E+14
$Y_{1b\ produced\ wood/4-10}$ (sej/ha/y)	5,31E+16	5,93E+14	6,44E+14	8,24E+14	6,63E+14	7,53E+14	5,74E+14
$Y_{2a\ standing\ wood}$ (sej/ha)	2,85E+16	2,96E+16	3,08E+16	3,21E+16	3,34E+16	3,45E+16	3,56E+16
$Y_{2b\ standing\ wood4-10}$ (sej/ha)	3,07E+17	3,15E+17	3,24E+17	3,33E+17	3,41E+17	3,48E+17	3,55E+17
$Y_{3a\ produced\ aboveground}$ (sej/ha)	7,16E+16	7,28E+16	7,40E+16	7,53E+16	7,66E+16	7,78E+16	7,91E+16
$Y_{3b\ produced\ aboveground/4-10}$ (sej/ha)	6,75E+17	6,84E+17	6,93E+17	7,01E+17	7,10E+17	7,18E+17	7,26E+17
$Y_{2\ removed}$ (sej/ha)	4,32E+16	0	0	0	1,04E+14	0	2,25E+14
$Y_{2b\ removed4-10}$ (sej/ha)	3,69E+17	0	0	0	7,61E+14	0	1,60E+15

Table F4 – continued 1

Item-Cum.	**1976**	**1977**	**1978**	**1979**	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**
$1/2_{cum35-04}$	8,87E+17	8,88E+17	8,88E+17	8,89E+17	8,90E+17	8,91E+17	8,92E+17	8,92E+17	8,93E+17	8,94E+17
$1_a/2_{a\ cum35-04}$	6,37E+17	6,37E+17	6,38E+17	6,38E+17	6,39E+17	6,39E+17	6,40E+17	6,41E+17	6,41E+17	6,42E+17
$1/2_{cum70-04}$	3,13E+16	3,21E+16	3,28E+16	3,36E+16	3,44E+16	3,51E+16	3,59E+16	3,67E+16	3,75E+16	3,82E+16
$1_a/2_{a\ cum70-04}$	2,25E+16	2,30E+16	2,35E+16	2,40E+16	2,46E+16	2,50E+16	2,57E+16	2,63E+16	2,69E+16	2,74E+16
3_{cum}	0	0	0	0	0	0	0	3,92E+13	3,92E+13	3,92E+13
$3_{ab\ cum}$	9,24E+13	1,34E+14	1,34E+14	1,34E+14	1,34E+14	1,34E+14	1,34E+14	2,35E+14	2,35E+14	2,35E+14
4_{cum}	3,01E+13	3,01E+13	8,88E+13	1,43E+14	1,43E+14	1,43E+14	1,68E+14	1,68E+14	1,68E+14	2,11E+14
5_{cum}	3,66E+15	3,73E+15	3,80E+15	3,86E+15	3,93E+15	3,99E+15	4,07E+15	4,13E+15	4,19E+15	4,25E+15
6_{cum}	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16
7_{cum}	1,59E+14	1,63E+14	1,67E+14	1,71E+14	1,75E+14	1,79E+14	1,82E+14	1,86E+14	1,90E+14	1,94E+14
8_{cum}	7,68E+14	7,87E+14	8,06E+14	8,24E+14	8,43E+14	8,62E+14	8,80E+14	8,99E+14	9,18E+14	9,37E+14
$9a_{cum}$	1,66E+14	1,66E+14	1,66E+14	1,66E+14	1,66E+14	1,67E+14	1,67E+14	1,67E+14	1,67E+14	1,67E+14
$9b_{cum}$	8,00E+14	8,01E+14	8,01E+14	8,02E+14	8,02E+14	8,02E+14	8,03E+14	8,03E+14	8,04E+14	8,04E+14
$10a_{cum}$	1,06E+16	1,06E+16	1,06E+16	1,06E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16
$10b_{cum}$	1,69E+16	1,69E+16	1,69E+16	1,69E+16	1,69E+16	1,69E+16	1,69E+16	1,69E+16	1,69E+16	1,69E+16
$11a_{cum}$	5,61E+13	5,61E+13	5,61E+13	6,42E+13	6,79E+13	6,79E+13	6,97E+13	6,97E+13	6,97E+13	6,97E+13
$11b_{cum}$	2,97E+14	2,97E+14	2,97E+14	3,41E+14	3,60E+14	3,60E+14	3,70E+14	3,70E+14	3,70E+14	3,70E+14
$12a_{cum}$	4,68E+15	4,68E+15	4,68E+15	5,39E+15	5,68E+15	5,68E+15	5,83E+15	5,83E+15	5,83E+15	5,83E+15
$12b_{cum}$	7,25E+15	7,25E+15	7,25E+15	8,33E+15	8,79E+15	8,79E+15	9,02E+15	9,02E+15	9,02E+15	9,02E+15
$R_{(35-04)}$	3,29E+16	3,37E+16	3,44E+16	3,53E+16	3,62E+16	3,69E+16	3,78E+16	3,86E+16	3,94E+16	4,02E+16
$R_{4-10\ (35-04)}$	6,38E+17	6,39E+17	6,40E+17	6,40E+17	6,41E+17	6,41E+17	6,42E+17	6,43E+17	6,43E+17	6,44E+17
$R_{prod.(35-04)}$	3,24E+16	3,32E+16	3,40E+16	3,48E+16	3,56E+16	3,63E+16	3,72E+16	3,80E+16	3,88E+16	3,96E+16
$R_{prod./4-10\ (35-04)}$	6,38E+17	6,39E+17	6,39E+17	6,40E+17	6,40E+17	6,41E+17	6,41E+17	6,42E+17	6,43E+17	6,43E+17
$R_{/y\ (70-04)}$	7,43E+14	7,94E+14	7,33E+14	9,06E+14	8,43E+14	7,04E+14	8,87E+14	8,44E+14	7,33E+14	7,95E+14
$R_{4-10/y\ (70-04)}$	5,13E+14	5,13E+14	5,31E+14	6,54E+14	6,04E+14	4,60E+14	7,33E+14	6,99E+14	5,30E+14	5,91E+14
$R_{prod./y\ (70-04)}$	7,43E+14	7,94E+14	7,33E+14	8,35E+14	8,12E+14	7,04E+14	8,72E+14	8,44E+14	7,33E+14	7,95E+14
$R_{prod.4-10/y\ (70-04)}$	5,13E+14	5,13E+14	5,31E+14	5,82E+14	5,74E+14	4,60E+14	7,18E+14	6,99E+14	5,30E+14	5,91E+14
N	3,66E+15	3,73E+15	3,80E+15	3,86E+15	3,93E+15	3,99E+15	4,07E+15	4,13E+15	4,19E+15	4,25E+15
$M_{produced}$	1,24E+16	1,25E+16	1,25E+16	1,25E+16	1,25E+16	1,26E+16	1,26E+16	1,26E+16	1,26E+16	1,26E+16
$M_{removed}$	3,53E+14	3,53E+14	3,53E+14	4,05E+14	4,28E+14	4,28E+14	4,40E+14	4,40E+14	4,40E+14	4,40E+14
$S_{produced}$	2,64E+16	2,64E+16	2,64E+16	2,64E+16	2,64E+16	2,65E+16	2,65E+16	2,65E+16	2,65E+16	2,65E+16
$S_{removed}$	1,15E+16	1,15E+16	1,15E+16	1,32E+16	1,39E+16	1,39E+16	1,43E+16	1,43E+16	1,43E+16	1,43E+16
$Y_{1a/y}$	8,65E+14	8,87E+14	8,31E+14	9,45E+14	9,22E+14	7,98E+14	1,00E+15	9,24E+14	8,18E+14	8,87E+14
$Y_{1b/y}$	5,83E+14	5,77E+14	5,74E+14	6,44E+14	6,59E+14	5,26E+14	8,04E+14	7,56E+14	5,90E+14	6,37E+14
Y_{2a}	3,66E+16	3,77E+16	3,87E+16	3,65E+16	3,62E+16	3,73E+16	3,76E+16	3,86E+16	3,96E+16	4,04E+16
Y_{2b4-10}	3,61E+17	3,67E+17	3,72E+17	3,47E+17	3,40E+17	3,46E+17	3,45E+17	3,50E+17	3,55E+17	3,59E+17
$Y_{3a\ prod.abovegr.}$	8,01E+16	8,12E+16	8,22E+16	8,47E+16	8,64E+16	8,75E+16	8,88E+16	8,98E+16	9,08E+16	9,16E+16
$Y_{3b\ prod.abovegr./4-10}$	7,32E+17	7,38E+17	7,43E+17	7,50E+17	7,57E+17	7,63E+17	7,68E+17	7,73E+17	7,79E+17	7,82E+17
$Y_{2\ removed}$	0	0	0	4,76E+15	1,99E+15	0	9,78E+14	0	0	0
$Y_{2b\ removed4-10}$	0	0	0	3,25E+16	1,33E+16	0	6,41E+15	0	0	0

Table F4 – continued 2

Item-Cum.	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**
$1/2_{cum35-04}$	8,95E+17	8,95E+17	8,96E+17	8,97E+17	8,98E+17	8,99E+17	8,99E+17	9,00E+17	9,01E+17	9,02E+17
$1_a/2_{a\ cum35-04}$	6,42E+17	6,43E+17	6,43E+17	6,44E+17	6,45E+17	6,45E+17	6,46E+17	6,46E+17	6,47E+17	6,47E+17
$1/2_{cum70-04}$	3,90E+16	3,98E+16	4,06E+16	4,13E+16	4,21E+16	4,29E+16	4,37E+16	4,44E+16	4,52E+16	4,60E+16
$1_a/2_{a\ cum70-04}$	2,80E+16	2,86E+16	2,91E+16	2,97E+16	3,03E+16	3,08E+16	3,15E+16	3,20E+16	3,26E+16	3,32E+16
3_{cum}	3,92E+13	3,92E+13	3,92E+13	3,92E+13	3,92E+13	3,92E+13	3,92E+13	3,92E+13	3,92E+13	3,92E+13
$3_{ab\ cum}$	2,35E+14	2,35E+14	2,35E+14	2,35E+14	2,35E+14	2,35E+14	2,74E+14	2,76E+14	2,76E+14	2,76E+14
4_{cum}	2,11E+14	2,11E+14	2,92E+14	2,92E+14	2,92E+14	2,92E+14	2,92E+14	2,92E+14	2,92E+14	2,92E+14
5_{cum}	4,30E+15	4,36E+15	4,43E+15	4,49E+15	4,56E+15	4,62E+15	4,68E+15	4,74E+15	4,82E+15	4,90E+15
6_{cum}	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16
7_{cum}	1,98E+14	2,02E+14	2,06E+14	2,10E+14	2,14E+14	2,17E+14	2,21E+14	2,25E+14	2,29E+14	2,33E+14
8_{cum}	9,55E+14	9,74E+14	9,93E+14	1,01E+15	1,03E+15	1,05E+15	1,07E+15	1,09E+15	1,11E+15	1,12E+15
$9a_{cum}$	1,67E+14	1,67E+14	1,67E+14	1,67E+14	1,68E+14	1,68E+14	1,68E+14	1,68E+14	1,68E+14	1,68E+14
$9b_{cum}$	8,04E+14	8,05E+14	8,05E+14	8,06E+14	8,06E+14	8,07E+14	8,07E+14	8,07E+14	8,08E+14	8,08E+14
$10a_{cum}$	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16
$10b_{cum}$	1,70E+16	1,70E+16	1,70E+16	1,70E+16	1,70E+16	1,70E+16	1,70E+16	1,70E+16	1,70E+16	1,70E+16
$11a_{cum}$	7,06E+13	7,15E+13	7,15E+13	7,21E+13	7,21E+13	8,11E+13	8,11E+13	8,11E+13	8,11E+13	8,23E+13
$11b_{cum}$	3,75E+14	3,79E+14	3,79E+14	3,83E+14	3,83E+14	4,32E+14	4,32E+14	4,32E+14	4,32E+14	4,38E+14
$12a_{cum}$	5,90E+15	5,97E+15	5,97E+15	6,02E+15	6,02E+15	6,82E+15	6,82E+15	6,82E+15	6,82E+15	6,92E+15
$12b_{cum}$	9,13E+15	9,23E+15	9,23E+15	9,32E+15	9,32E+15	1,06E+16	1,06E+16	1,06E+16	1,06E+16	1,07E+16
$R_{(35-04)}$	4,09E+16	4,18E+16	4,26E+16	4,34E+16	4,42E+16	4,50E+16	4,58E+16	4,66E+16	4,74E+16	4,82E+16
$R_{4-10\ (35-04)}$	6,44E+17	6,45E+17	6,46E+17	6,46E+17	6,47E+17	6,47E+17	6,48E+17	6,49E+17	6,49E+17	6,50E+17
$R_{prod.(35-04)}$	4,03E+16	4,12E+16	4,20E+16	4,28E+16	4,36E+16	4,43E+16	4,52E+16	4,59E+16	4,67E+16	4,75E+16
$R_{prod./4-10\ (35-04)}$	6,44E+17	6,44E+17	6,45E+17	6,46E+17	6,46E+17	6,47E+17	6,47E+17	6,48E+17	6,49E+17	6,49E+17
$R_{/y\ (70-04)}$	7,63E+14	8,47E+14	8,57E+14	7,62E+14	7,94E+14	8,49E+14	8,20E+14	7,24E+14	8,06E+14	7,85E+14
$R_{4-10/y\ (70-04)}$	5,62E+14	5,97E+14	6,35E+14	5,56E+14	6,37E+14	6,35E+14	6,50E+14	5,71E+14	5,89E+14	5,60E+14
$R_{prod./y\ (70-04)}$	7,56E+14	8,40E+14	8,57E+14	7,56E+14	7,94E+14	7,67E+14	8,20E+14	7,24E+14	8,06E+14	7,75E+14
$R_{prod.4-10/y\ (70-04)}$	5,55E+14	5,90E+14	6,35E+14	5,50E+14	6,37E+14	5,54E+14	6,50E+14	5,71E+14	5,89E+14	5,49E+14
N	4,30E+15	4,36E+15	4,43E+15	4,49E+15	4,56E+15	4,62E+15	4,68E+15	4,74E+15	4,82E+15	4,90E+15
$M_{produced}$	1,27E+16	1,27E+16	1,27E+16	1,27E+16	1,28E+16	1,28E+16	1,28E+16	1,28E+16	1,29E+16	1,29E+16
$M_{removed}$	4,45E+14	4,51E+14	4,51E+14	4,55E+14	4,55E+14	5,13E+14	5,13E+14	5,13E+14	5,13E+14	5,20E+14
$S_{produced}$	2,65E+16	2,66E+16	2,66E+16	2,66E+16	2,66E+16	2,66E+16	2,66E+16	2,66E+16	2,66E+16	2,67E+16
$S_{removed}$	1,44E+16	1,46E+16	1,46E+16	1,47E+16	1,47E+16	1,67E+16	1,67E+16	1,67E+16	1,67E+16	1,69E+16
$Y_{1a/y}$	8,55E+14	9,56E+14	9,46E+14	8,69E+14	8,93E+14	8,69E+14	9,10E+14	8,09E+14	9,12E+14	9,08E+14
$Y_{1b/y}$	6,34E+14	6,80E+14	6,63E+14	6,38E+14	7,05E+14	6,32E+14	7,13E+14	6,31E+14	6,62E+14	6,49E+14
Y_{2a}	4,11E+16	4,18E+16	4,28E+16	4,36E+16	4,45E+16	4,19E+16	4,29E+16	4,40E+16	4,51E+16	4,57E+16
Y_{2b4-10}	3,61E+17	3,63E+17	3,68E+17	3,71E+17	3,75E+17	3,50E+17	3,54E+17	3,60E+17	3,66E+17	3,67E+17
$Y_{3a\ prod.abovegr.}$	9,28E+16	9,39E+16	9,49E+16	9,61E+16	9,70E+16	9,98E+16	1,01E+17	1,02E+17	1,03E+17	1,04E+17
$Y_{3b\ prod.abovegr./4-10}$	7,87E+17	7,92E+17	7,97E+17	8,02E+17	8,07E+17	8,13E+17	8,18E+17	8,23E+17	8,29E+17	8,34E+17
$Y_{2\ removed}$	4,66E+14	4,65E+14	0	3,64E+14	0	5,34E+15	0	0	0	6,57E+14
$Y_{2b\ removed4-10}$	2,93E+15	2,89E+15	0	2,21E+15	0	3,20E+16	0	0	0	3,76E+15

Table F4 – continued 3

Item-Cum.	1996	1997	1998	1999	2000	2001	2002	2003	2004
$1/2_{cum35-04}$	9,03E+17	9,03E+17	9,04E+17	9,05E+17	9,06E+17	9,07E+17	9,08E+17	9,09E+17	9,09E+17
$1a/2a_{cum35-04}$	6,48E+17	6,49E+17	6,49E+17	6,50E+17	6,51E+17	6,51E+17	6,52E+17	6,53E+17	6,53E+17
$1/2_{cum70-04}$	4,69E+16	4,77E+16	4,85E+16	4,93E+16	5,02E+16	5,10E+16	5,21E+16	5,29E+16	5,37E+16
$1a/2_{a\ cum70-04}$	3,39E+16	3,44E+16	3,51E+16	3,57E+16	3,63E+16	3,69E+16	3,77E+16	3,84E+16	3,90E+16
3_{cum}	3,92E+13	3,92E+13	3,92E+13	3,92E+13	3,11E+14	3,11E+14	5,50E+14	1,01E+15	1,01E+15
$3_{ab\ cum}$	2,76E+14	2,76E+14	2,76E+14	2,76E+14	3,73E+14	4,26E+14	4,93E+14	8,06E+14	8,06E+14
4_{cum}	2,92E+14	3,36E+14	3,65E+14	3,65E+14	3,65E+14	4,31E+14	4,61E+14	5,99E+14	6,17E+14
5_{cum}	4,98E+15	5,04E+15	5,08E+15	5,14E+15	5,21E+15	5,27E+15	5,34E+15	5,41E+15	5,48E+15
6_{cum}	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16	1,05E+16
7_{cum}	2,37E+14	2,41E+14	2,45E+14	2,48E+14	2,52E+14	2,56E+14	2,60E+14	2,64E+14	2,68E+14
8_{cum}	1,14E+15	1,16E+15	1,18E+15	1,20E+15	1,22E+15	1,24E+15	1,26E+15	1,27E+15	1,29E+15
$9a_{cum}$	1,68E+14	1,68E+14	1,69E+14	1,69E+14	1,69E+14	1,69E+14	1,69E+14	1,69E+14	1,69E+14
$9b_{cum}$	8,09E+14	8,09E+14	8,09E+14	8,10E+14	8,10E+14	8,10E+14	8,11E+14	8,11E+14	8,11E+14
$10a_{cum}$	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,08E+16
$10b_{cum}$	1,70E+16	1,70E+16	1,71E+16	1,71E+16	1,71E+16	1,71E+16	1,71E+16	1,71E+16	1,71E+16
$11a_{cum}$	8,23E+13	8,23E+13	8,23E+13	8,23E+13	8,23E+13	8,23E+13	8,23E+13	8,23E+13	2,17E+14
$11b_{cum}$	4,38E+14	4,38E+14	4,38E+14	4,38E+14	4,38E+14	4,38E+14	4,38E+14	4,38E+14	1,18E+15
$12a_{cum}$	6,92E+15	6,92E+15	6,92E+15	6,92E+15	6,92E+15	6,92E+15	6,92E+15	6,92E+15	1,93E+16
$12b_{cum}$	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16	1,07E+16	2,97E+16
$R_{(35-04)}$	4,91E+16	4,99E+16	5,07E+16	5,15E+16	5,26E+16	5,35E+16	5,49E+16	5,63E+16	5,84E+16
$R_{4-10\ (35-04)}$	6,50E+17	6,51E+17	6,52E+17	6,52E+17	6,53E+17	6,54E+17	6,55E+17	6,56E+17	6,58E+17
$R_{prod.(35-04)}$	4,84E+16	4,92E+16	5,00E+16	5,08E+16	5,19E+16	5,28E+16	5,42E+16	5,56E+16	5,64E+16
$R_{prod./4-10\ (35-04)}$	6,50E+17	6,50E+17	6,51E+17	6,52E+17	6,52E+17	6,53E+17	6,54E+17	6,55E+17	6,56E+17
$R_{/y\ (70-04)}$	9,18E+14	8,29E+14	8,18E+14	7,84E+14	1,13E+15	8,87E+14	1,35E+15	1,47E+15	2,05E+15
$R_{4-10/y\ (70-04)}$	7,09E+14	6,22E+14	6,85E+14	6,18E+14	6,86E+14	7,24E+14	9,21E+14	1,08E+15	1,94E+15
$R_{prod./y\ (70-04)}$	9,18E+14	8,29E+14	8,18E+14	7,84E+14	1,13E+15	8,87E+14	1,35E+15	1,47E+15	7,93E+14
$R_{prod.4-10/y\ (70-04)}$	7,09E+14	6,22E+14	6,85E+14	6,18E+14	6,86E+14	7,24E+14	9,21E+14	1,08E+15	6,84E+14
N	4,98E+15	5,04E+15	5,08E+15	5,14E+15	5,21E+15	5,27E+15	5,34E+15	5,41E+15	5,48E+15
$M_{produced}$	1,29E+16	1,29E+16	1,29E+16	1,30E+16	1,30E+16	1,30E+16	1,30E+16	1,31E+16	1,31E+16
$M_{removed}$	5,20E+14	5,20E+14	5,20E+14	5,20E+14	5,20E+14	5,20E+14	5,20E+14	5,20E+14	1,40E+15
$S_{produced}$	2,67E+16	2,67E+16	2,67E+16	2,67E+16	2,67E+16	2,67E+16	2,67E+16	2,67E+16	2,67E+16
$S_{removed}$	1,69E+16	1,69E+16	1,69E+16	1,69E+16	1,69E+16	1,69E+16	1,69E+16	1,69E+16	4,70E+16
$Y_{1a/y}$	1,01E+15	9,14E+14	8,90E+14	8,71E+14	1,22E+15	9,73E+14	1,45E+15	1,55E+15	9,12E+14
$Y_{1b/y}$	7,75E+14	6,64E+14	7,26E+14	6,79E+14	7,50E+14	7,57E+14	9,75E+14	1,08E+15	7,64E+14
Y_{2a}	4,68E+16	4,76E+16	4,86E+16	4,96E+16	5,08E+16	5,18E+16	5,31E+16	5,46E+16	5,54E+16
Y_{2b4-10}	3,71E+17	3,75E+17	3,79E+17	3,83E+17	3,87E+17	3,91E+17	3,96E+17	4,00E+17	4,03E+17
$Y_{3a\ prod.abovegr.}$	1,05E+17	1,06E+17	1,07E+17	1,08E+17	1,09E+17	1,10E+17	1,12E+17	1,13E+17	1,96E+17
$Y_{3b\ prod.abovegr./4-10}$	8,38E+17	8,42E+17	8,46E+17	8,50E+17	8,54E+17	8,59E+17	8,63E+17	8,67E+17	1,30E+18
$Y_{2\ removed}$	0	0	0	0	0	0	0	0	8,16E+16
$Y_{2b\ removed4-10}$	0	0	0	0	0	0	0	0	4,29E+17

APPENDIX F5: Review of calculations: Calculation of flows and storages in physical units and calculation (or source) of applied UEVs.

Physical units		***UEV***	
1 EToa* (J/ha/y)		sej/J	
= ETo (mm)	*(ARSO)*	= 27984 *(Brown, 1978)*	
** % lowered at drought*	*(Table 4)*		
** m/mm*	*0,001*		
** m^2/ha*	*10000*		
** density of water (kg/m^3)*	*1000*		
** Gibbs free energy (J/kg)*	*4940*		
2 Precipitation* (J/ha/y)		sej/J	
= ETo (mm)	*(ARSO)*	= 18199 *(Odum, 1996)*	
** m/mm*	*0,001*		
** m^2/ha*	*10000*		
** density of water (kg/m^3)*	*1000*		
** Gibbs free energy (J/kg)*	*4940*		
3 Run-in of gw* (J/ha/y)		sej/J	
= IF(water$_{@soil\ (y)}$ - water$_{@soil\ (y+1)}$ + precipitation - ET$_{oa}$)>0 THEN (water$_{@soil\ (y)}$ - water$_{@\ soil\ (y+1)}$ + precipitation – ET$_{oa}$) ELSE 0 (mm)		*= UEV (rain chem. potential)*	*(row 2)*
		**average annual precipitation (J/ha/y)* (ARSO)	
** m/mm*	*0,001*	*/ average annual runoff (J/ha/y)*	
** m^2/ha*	*10000*		*(this study, row 18)*
** density of water (kg/m^3)*	*1000*		
** Gibbs free energy (J/kg)*	*4940*		
4 White-frost (J/ha/y)		sej/J	
= d-wf_4-7	*(ARSO)*	*= average UEV (NPP)*	*(row 15)*
** NPP/y (J/ha/y)*	*(row 15)*		
** days per growing season*	7/214 *(estimation based on data about leaf development)*		
5 Leached N (g/ha/y)		sej/g	
= leaves/y (y-1)	*(row 14)*	*= (UEV (fixed N)*	*(row 17a)*
** %N/leaf litter*	*0,035* *(Uri et al., 2003)*	**(% fixed N/soil$_{(y-1)}$*	*0,6* *(initial value assumed)*
** leaching intensity*	*0,627* *(calculated to sustain nitrogen concentration in the soil)*	*+ part leached per year)*	*0,007* *(estimated)*
		+(UEV (mineral N)	*2,41E+09 sej/g* *(Brandt-Williams, 2002)*
		**(% fixed N/soil$_{(y-1)}$*	*0,4* *(initial value assumed)*
		- part leached per year))	*0,007* *(estimated)*
6 Plantings/y (J/ha/y)		sej/J	
= biomass (kg)	*(this study)*	*= 1,96E+04*	
**g/kg*	*1000*	*(weighted average of emergy inputs/energy of plantings)*	
**J/g*	*16744* *(Bardi, 2002)*		
7 Wood for roads/y (J/ha/y)		sej/J	
= average piece of wood (kg)	*1,96*	*= 1,96E+04*	
** number of pieces needed/55,1m road*	*689*	*(UEV of removed wood in the year 1970)*	
** road width (m)*	*2*		
/ lifetime (years)	*200* *(estimation)*		
**g/kg*	*1000*		
**J/g*	*16744* *(Bardi, 2002)*		
8 Gravel for roads/y (g/ha/y)		sej/g	
= depth of gravel/lifetime (m)	*0,3* *(Kolenko, personal comm.)*	*= 1,0E+09* *(Odum, 1996)*	
** road width (m)*	*2*		
**road length (m)*	*55,1* *(Forest Management plans)*		
** gravel density (kg/m^3)*	*1700*		
/ gravel lifetime (years)	*300*		
**g/kg*	*1000*		

9 Machinery (g/ha/y)		sej/g
= (*work: tractor (hours/y)* *(sum of planting, care, cutting…)*		= *6,70+09 sej/g (Doherty, 1995)*
* *weight (kg)*	*5000 (Kolenko, personal comm.)*	
* *(g/kg)*	*1000*	
/lifetime (hours))	*15000 (Doherty, 1995)*	
+ *(work: chain-saw (hours/y)* *(sum of thinning, felling, cutting)*		
* *weight (kg)*	*5 (estimation)*	
* *(g/kg)*	*1000*	
/ lifetime (hours))	*2000 (Doherty, 1995)*	
10 Petrol (J/ha/y)		sej/J
= *(work: tractor (hours/y)* *(sum of planting, care, cutting…)*		*= 4,79E+04 (Doherty, 1995)*
* *fuel use (L/hour)*	*5 (Kolenko, personal comm.)*	
* *energy content (J/L)*	*3,95E+07*	
+ *(work: chain-saw (hours/y)* *(sum of thinning, felling, cutting)*		
* *fuel use (L/hour)*	*0,5 (estimation)*	
* *energy content (J/L)*	*3,95E+07*	
11 Human work/y (J/ha/y)		sej/hour
= *work (hours/y)* *(sum of planting, care, cutting...)*		*= 2,97E+13 (this study, Appendix E)*
12 Services/y (USD/ha/y)		sej/USD
= *(seedlings – growing up (USD/ha)* *(own calculation: work, environmental work, watering, machinery, fuel, and seeds per 50 m2 needed to grow up seedlings)*		*= 6,19E+12 (this study, Appendix E)*
+gravel (SIT/m^3/y)[§]	*4864 (price in local gravel pit + transport)*	
+work (SIT/hour/y)	*1471,5 (SURS: average Slovenian wage; 2002)*	
+fuel (SIT/L/y)	*224,6 (SURS; 2006)*	
+machinery (SIT/kg/y))	*2000 (machinery prices)*	
* *exchange rate (USD/SIT)*	*221,1 (SURS; 2002)*	
13 Aboveground wood/y (J/ha/yr)		sej/J
= *annual aboveground. increment (m^3/ha/y)* *(this study)*		= *(R+N+M$_{produced}$+S$_{produced}$ (sej))*
* *density dry wood (kg/m^3)*	*510 (Wagenführ, 1996)*	*/ (Aboveground wood/y (J/ha/yr))*
* *(g/kg)*	*1000*	
* *energy content (J/g)*	*16744 (Bardi, 2002)*	
14 Leaves/y (g/ha/y)		sej/g
= *NPP/y (kg/ha/y)*	*(row 15)*	= *(R+N+M$_{produced}$+S$_{produced}$ (sej))*
* *% invested into leaves*	*0,2048 (Eschenbach, 1995)*	*/ (Leaves/y (g/ha/y))*
* *(g/kg)*	*1000*	
15 NPP/y (J/ha/y)		sej/J
= *aboveground wood/y (J/ha/y)*	*(row 13)*	= *(R+N+M$_{produced}$+S$_{produced}$ (sej))*
/ part of NPP/y invested into wood	*0,2208 (Eschenbach, 1995)*	*/ (NPP/y (J/ha/y))*
16 Aboveground biomass/y (J/ha/y)		sej/J
= *aboveground wood/y (J/ha/y)*	*(row 13)*	= *(R+N+M$_{produced}$+S$_{produced}$ (sej))*
* *part of NPP/y invested into aboveground biomass*	*0,6235 (Eschenbach, 1995)*	*/ (Aboveground biomass/y (J/ha/y))*
17a N_2 fixed/y (g/ha/y)		sej/g
= *annual aboveground increment (m^3/ha/y)* *(this study)*		= *UEV(NPP/Y)* *(row 15)*
* *density dry wood (kg/m^3)*	*510 (Wagenführ, 1996)*	* *NPP (g) needed to fix 1g of N* *18,8 (Borman and Gordon, 1984)*
* *(g/kg)*	*1000*	
* *N in alder tissue (g/g)*	*0,02 (Uri et al., 2003)*	
* *part of N fixed*	*0,7 (Cote and Camire, 1985; Middelhoff, 2000)*	

[§] Slovenian Tolar (SIT) was Slovenian currency in till the end of 2006.

17b N_2 mineralized/y used for growth (g/ha/y)
= annual aboveground increment (m³/ha/y) *(this study)*
** density dry wood (kg/m³)* *510 (Wagenführ, 1996)*
** (g/kg)* *1000*
** N in alder tissue (g/g)* *0,02 (Uri et al., 2003)*
** part of N fixed* *0,3 (Cote and Camire, 1985; Middelhoff, 2000)*

sej/g
= 2,41E+09 sej/g (Brandt-Williams, 2002)

18 Run out/y (J/y)
= IF(water$_{@soil\ (y)}$ - water$_{@soil\ (y+1)}$ + precipitation - ET$_{oa}$)<0 THEN (water$_{@soil\ (y)}$ - water$_{@\ soil\ (y+1)}$ + precipitation - ET$_{oa}$) ELSE 0 (mm)
** m/mm* *0,001*
** m²/ha* *10000*
** density of water (kg/m³)* *1000*
** Gibbs free energy (J/kg)* *4940*

sej/J
= UEV (rain chem. potential)
** rain (J/ha/y) (ARSO)*
/ annual run-out (J/ha/y) (this study)

19 Water@stand (J/ha)
= (depth of saturation zone (m) *(calculated from Ledava level)*
** area (m²)* *10000*
** water content in saturated zone* *0,35 (Brilly and Šraj, 2000))*
+ (depth of unsaturated zone (m) *(calculated from Ledava level)*
** area (m²)* *10000*
** water content in unsaturated zone))* *0,044 (Brilly and Šraj, 2000)*
** density of water (kg/m³)* *1000*
** Gibbs free energy (J/kg)* *4940*

sej/J
= IF (rain-ETоa)<0 THEN
(average UEV(water@stand))(water@stand (J) - rain (J) +ETоa (J)) / water@stand (J))*
ELSE
((rain (J)-ETоa (J))/ water@stand (J))
**UEV (rain)*(rain (J)/(rain (J)-ETоa (J)))+*
(water@stand (J) -rain (J) +ETоa (J))/(Water@stand (J)
** average UEV(water@stand))*

average UEV(water@stand) = ((higher of rain and ETоa (sej)+run-in (sej))(wate@stand*%annual inflow to groundwater)*

%annual inflow to groundwater: 0,168 (this study)

20 Standing wood (J/ha)
= standing wood biomass (m³/ha) *(this study)*
** density dry wood (kg/m³)* *510 (Wagenführ, 1996)*
** (g/kg)* *1000*
** energy content (J/g)* *16744 (Bardi, 2002)*

sej/J
= (R_{cum}+N_{cum}+$M_{produced-cum}$+$S_{produced-cum}$ (sej))
/ (standing wood +removed wood-cum (J/ha))

21 Total standing biomass (J/ha)
= standing wood (J/ha) *(row 19)*
/ (part of wood in aboveground biomass) *0,621 (Eschenbach, 1995)*

sej/J
= (R_{cum}+N_{cum}+$M_{produced-cum}$+$S_{produced-cum}$ (sej))
/ (total standing biomass (J/ha))

22 Organic matter in the soil (J/ha)
= (kg/ha) *51861*
(calculated based on data from Kalan et al., 1988; assumed constant value)
** (g/kg)* *1000*
** energy content (J/g)* *16744 (Bardi, 2002)*

sej/J
= (R_{cum}+N_{cum}+$M_{produced-cum}$+$S_{produced-cum}$ (sej))
/ (organic matter in the soil (J/ha))

23 Removed wood/y (J/ha/yr)
= removed wood (m³/ha) *(Management Plans)*
** density dry wood (kg/m³)* *510 (Wagenführ, 1996)*
** (g/kg)* *1000*
** energy content (J/g)* *16744 (Bardi, 2002)*

sej/J
= (R_{cum}+N_{cum}+$M_{produced-cum}$+$S_{produced-cum}$+ $R_{removed-cum}$+$S_{removed-cum}$ (sej)))
/ (removed wood (J/ha))

** The same formulas were valid also for attributes calculated over different period of time.*

APPENDIX G: Temporary dynamic model in STELLA (map/model level)

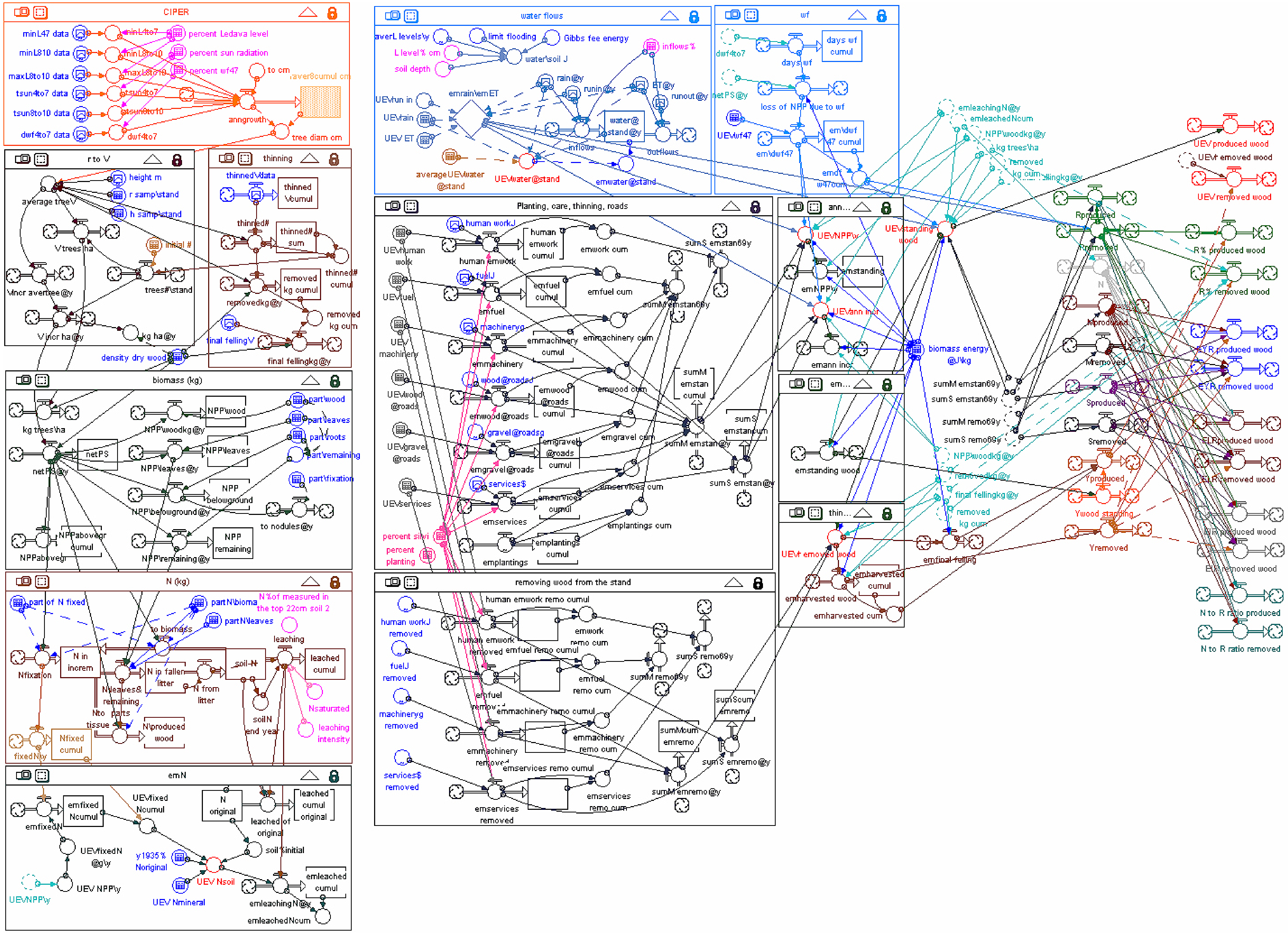


Figure G1 *The temporary dynamic model constructed and used in this study.*

APPENDIX H: Selected simulations and sensitivity analyses of the temporary dynamic model

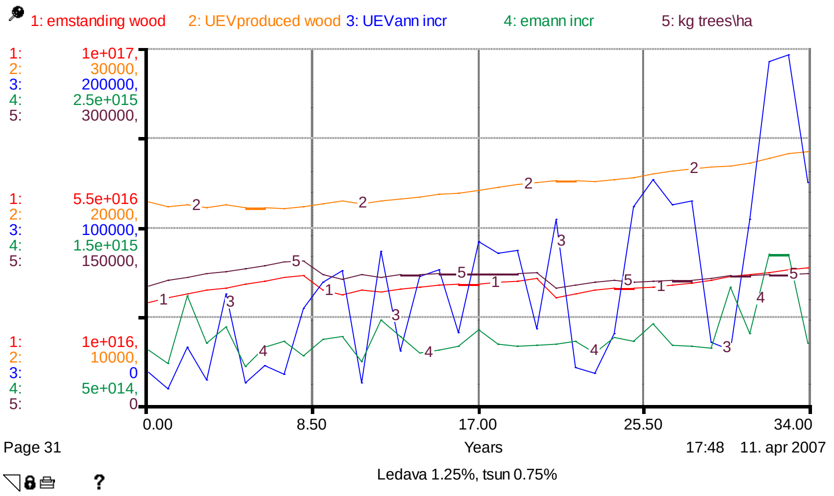


Figure H1 *Comparison of emergy of wood storages (1) and flows (4), UEVs (2, 3) and total produced biomass (5) under 25% increased Ledava River level and 25% decreased sun radiation energy. (1, emstanding wood: emergy stored in standing wood; 2, UEV produced wood: UEV of total produced aboveground wood; 3, UEVann incr: UEV of annual increments; 4, emann incr: emergy invested into increments; 5, kgtrees\ha: weight of standing aboveground wood).*

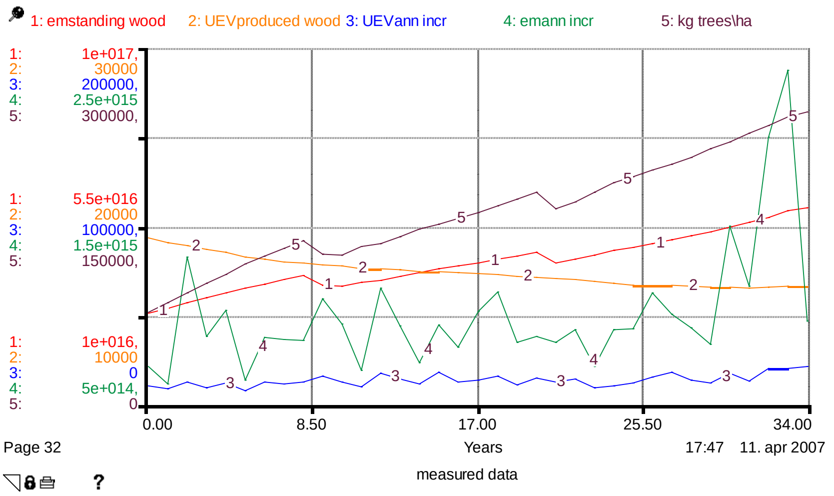


Figure H2 *Comparison of emergy of the storages (1) and flows (4), UEVs (2, 3) and the total produced biomass (5) under measured data (symbols are explained in the Figure H1).*

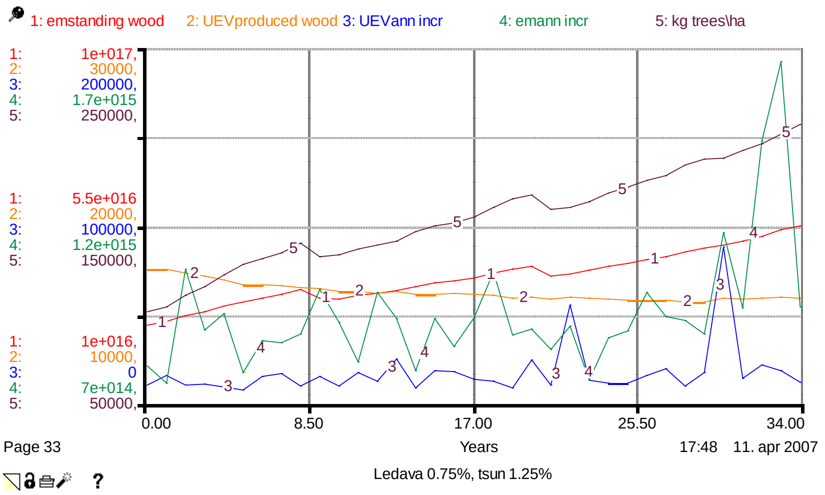


Figure H3 *Comparison of emergy of the storages (1) and flows (4), UEVs (2, 3) and total produced biomass (5) under 25% decreased Ledava River level and 25% increased sun radiation energy (symbols are explained in the Figure H1).*

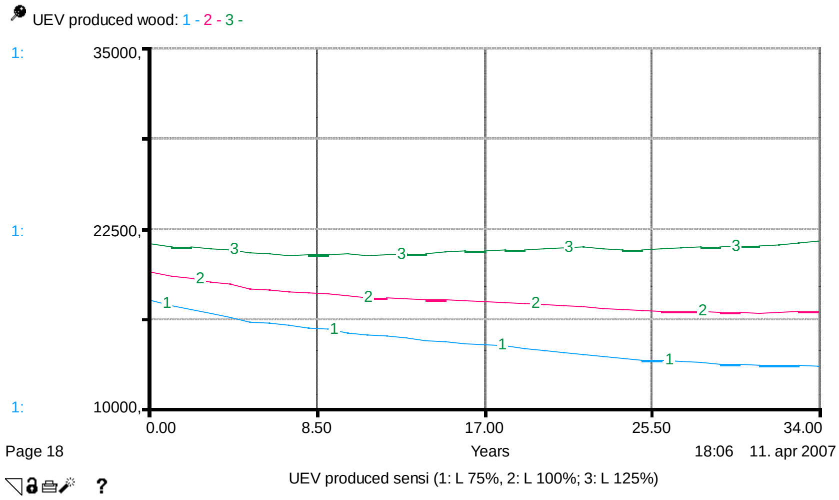


Figure H4 *Comparison of UEVs of the produced wood calculated at source conditions (2) and at 25% lower (1) and 25% higher Ledava levels (L) (3).*

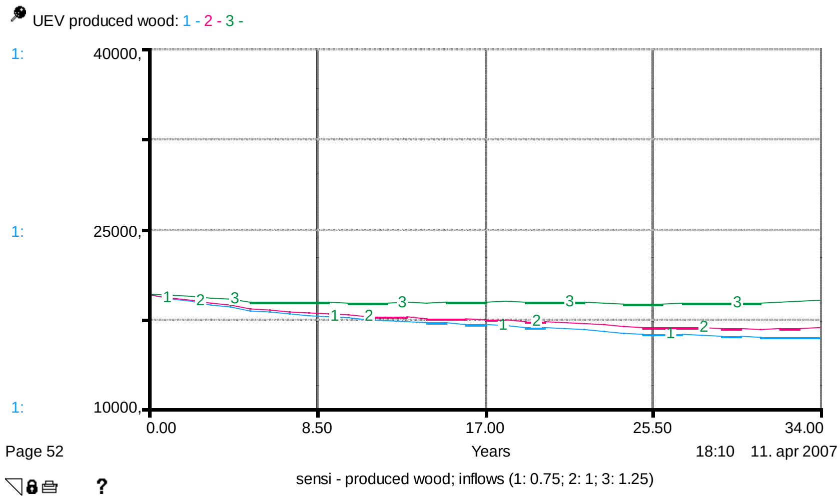


Figure H5 *Comparison of UEVs of the produced wood calculated at source conditions (2) and at 5E+09 J lower (1) and 5E+09 J higher (3) inflows of chemical energy of water (precipitation and run-in).*

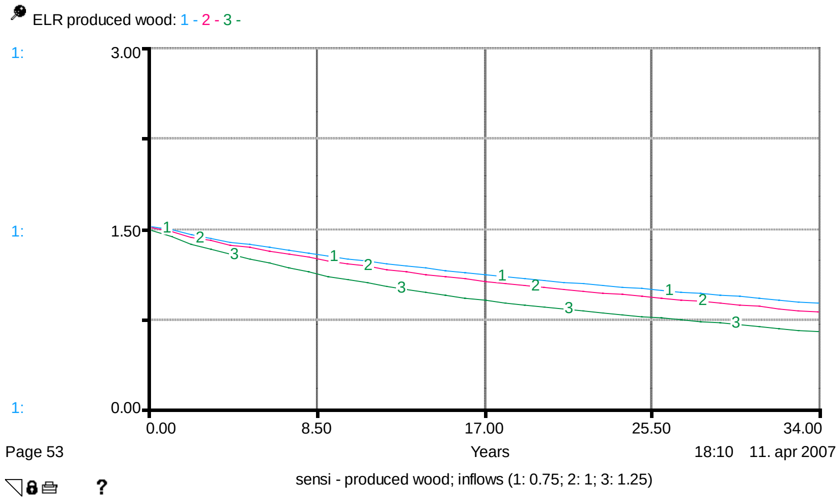


Figure H6 *Comparison of ELR of the produced wood calculated at source conditions (2) and at 5E+09 J lower (1) and 5E+09 J higher (3) inflows of chemical potential energy of water (precipitation and run-in).*

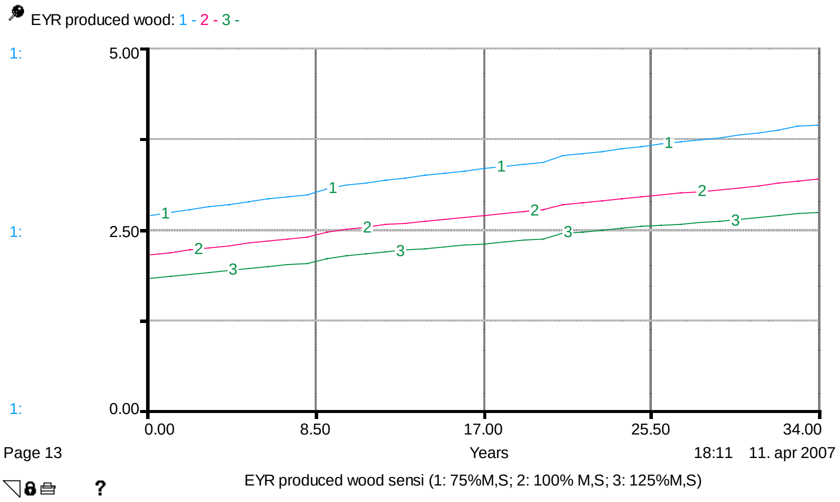


Figure H7 *Comparison of EYR of the produced wood calculated at source conditions (2) and at 25% lower (1) and 25% higher (3) investments of purchased emergy (M and S).*

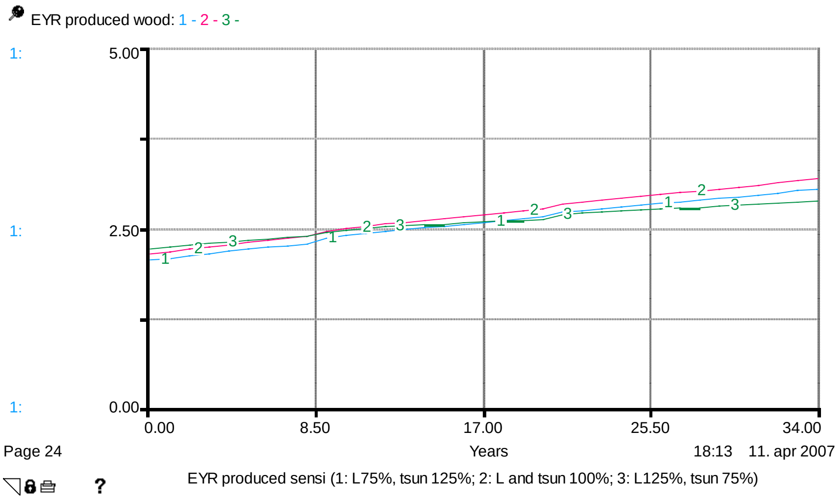


Figure H8 *Comparison of EYR of the produced wood calculated at source conditions (2), at 25% lower Ledava level (L) and 25% higher sun radiation (tsun) (1) and vice versa (3).*

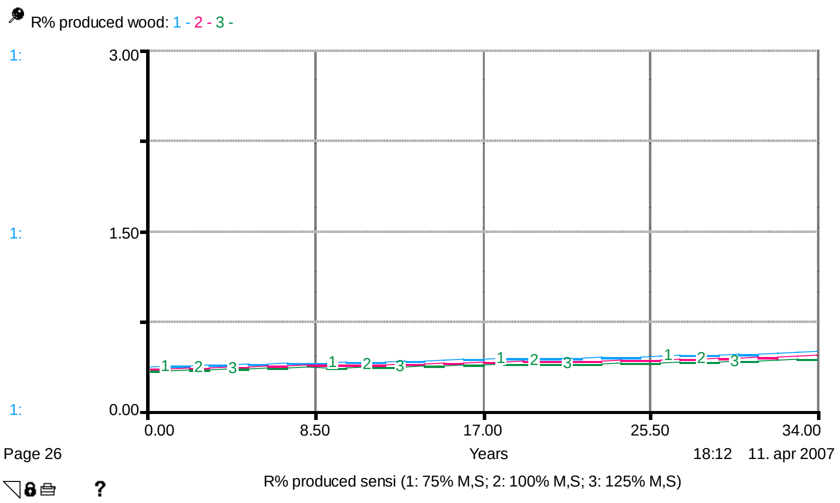


Figure H9 *Comparison of %R of the produced wood calculated at source conditions (2); at 25% lower (1) and 25% higher (3) purchased (M and S) investments.*

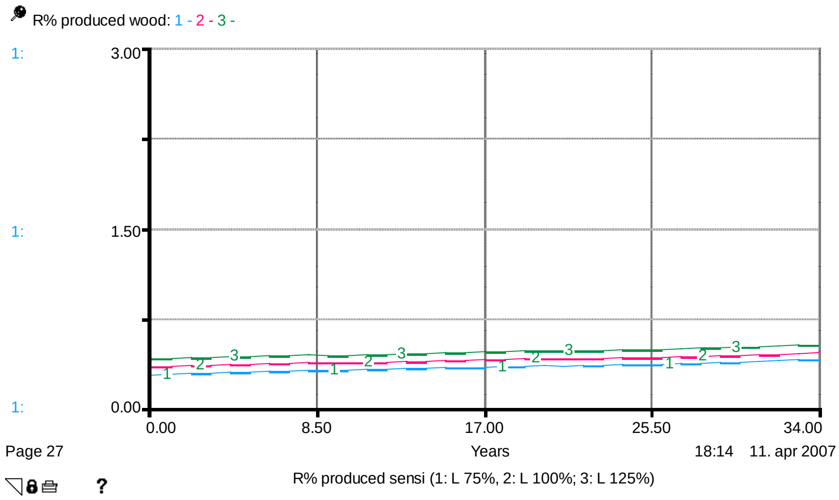


Figure H10 *Comparison of %R of the produced wood calculated at source conditions (2), at 25% lower Ledava level (1) and 25% higher Ledava level (L) (3).*