*Send to Fort Smith
file copy*
VULNERABILITY AND ADAPTATION TO GLOBAL

CLIMATE CHANGE: THE ESTONIAN NATIONAL

REPORT

*DE-FC02-94PO30115
DOE/PO/30115--T1-Pt.2*

RECEIVED

JUN 09 1999

OSTI

A Synthesis of Results from the U.S. Country Studies

Program

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *ph*

MASTER

PROCESSED FROM BEST AVAILABLE COPY *PH*

April 1996

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

CONTENTS

INTRODUCTION TO CLIMATE CHANGE ISSUES IN ESTONIA	2
SCENARIOS USED IN THE V&A ASSESSMENT	7
Baseline Climate Scenarios	7
GCM Climate Change Scenarios	8
Incremental Scenarios	11
Baseline Scenario of Population and GNP Growth	12
Sea Level Rise Scenarios	12
Paleoecological Approaches	13
<i>Methods</i>	13
<i>Analysis of Estonia</i>	15
<i>Discussion</i>	18
ESTONIA'S V&A ASSESSMENT FOR THE AGRICULTURE SECTOR	19
Introduction	19
Methods Used for the V&A Assessment	20
<i>Crop Models Used in the Assessment</i>	20
<i>Selection of Study Sites</i>	22
Results of the V&A Assessment	25
<i>Barley</i>	25
<i>Herbage</i>	29
<i>Potato</i>	30
<i>Aggregate Crop Model Results</i>	31
<i>Adaptation Options</i>	32
<i>Discussion</i>	34
ESTONIA'S V&A ASSESSMENT FOR THE FORESTRY SECTOR	36
Preliminary Screening	37
Methods Used for the V&A Assessment	39
<i>Forest Ecosystem Models Used in the Assessment</i>	39
<i>Climate Change Scenarios</i>	41
<i>Selection of Study Sites</i>	42
Results of the V&A Assessment	43
Economic Analyses	47
Discussion and Conclusions	52

ESTONIA'S V&A ASSESSMENT FOR THE WATER RESOURCES SECTOR	55
Methods Used for the V&A Assessment	55
<i>Hydrologic and Water Resources Methodologies Used in the Assessment</i>	<i>55</i>
<i>Selection of Study Sites</i>	<i>57</i>
Results of the V&A Assessment	59
<i>Results of the Hydrologic Vulnerability Assessment</i>	<i>59</i>
<i>Results of Water Resources Supply and Demand Models by Climate Change Scenario</i>	<i>64</i>
Discussion and Conclusions	66
Modelling the Influence of Climate Change on Groundwater Regime in Estonia	67
Data Sources	68
Methods	69
Natural Fluctuations	70
Modelling the Impact of Climate Change on Groundwater Level	72
Groundwater Consumption and Quality in the Coastal Areas	75
Discussion and Conclusions	76
 ESTONIA'S V&A ASSESSMENT FOR THE COASTAL RESOURCES SECTOR	 78
Methods Used for the V&A Assessment	79
<i>Sea-Level Rise Methodologies Used in the Assessment</i>	<i>79</i>
<i>Selection of Study Sites</i>	<i>82</i>
<i>Methodology for Economic Analyses</i>	<i>85</i>
<i>Adaptation Alternatives Evaluated Using the Methodology</i>	<i>85</i>
Results and Discussion of the V&A Assessment	86
Land Loss Analysis Results	86
Aggregate Assessment Results	96
Adaptation Options	97
Conclusions	98
 INTEGRATION ACROSS SECTORS AND ASSESSMENT OF RELATIVE	
VULNERABILITY	100
ACKNOWLEDGEMENTS	102
REFERENCES	103

VULNERABILITY AND ADAPTATION TO GLOBAL CLIMATE CHANGE: THE ESTONIAN NATIONAL REPORT

Are Kont,¹ Jaan-Mati Punning,¹ Mare Ainsaar,² Jaak Jaagus,² Arvo Järvet,²,
Jaan Klõšeiko,¹ Tiiu Koff,¹ Malle Mandre,¹ Hugo Roostalu,³ Toomas Tamm³

1 Institute of Ecology

2 University of Tartu

3 Estonian Agriculture University

Summary

Because of its geography, wide coastal areas, water resources, forests, and wetlands, the environment of Estonia is sensitive to climate change and sea level rise. Therefore, the vulnerability and adaptation assessment focused on these sectors. This report gives the results of our study. GCM-based and incremental climate change scenarios are used for V&A assessment in Estonia. The results of five GCMs provided by NCAR are available, and four of them (GISS, CCCM, GFDL30, GFDL transient) are chosen for the assessment in Estonia. The CERES-Barley model is used to assess crop productivity in four long-term (1966-1987) barley field trials situated on different types of soils in different parts of Estonia. The SPUR-2 model which was expected to use to assess herbage sensitivity to climate change doesn't fit Estonia. To estimate the responses of forests to proposed climate change scenarios, five study sites with relatively species rich forest stands and with different types of climate (continental and moderately maritime) are selected and the simple version of the Forest Gap Model is used. The Holdridge Life Zones Classification Models are also used to determine the potential evapotranspiration ratio for different tree species and the multiplier for temperature as a function of the forest growth. The WatBal model is used in water resources vulnerability assessment for three rivers with different hydrological regimes and landscape conditions. Additionally, the impact of climate change on groundwater fluctuations is considered using the relationships between precipitation, runoff and groundwater level. A sea level rise of 1.0 m is used to evaluate the responses of the natural and socio-economic systems in the low-lying coastal territories in five different study areas. In addition, an analysis is conducted using paleogeographical data from Estonia and neighboring areas. The data indicate that between 7.000 and 5.000 years ago (Holocene "climatic optimum") the temperatures in Estonia were similar to predicted future temperatures. Thus we can compare the state of ecosystems in the past with those predicted for future global climate change.

INTRODUCTION TO CLIMATE CHANGE ISSUES IN ESTONIA

Estonia is the northernmost Baltic country in Europe (between 57.30° and 59.49°N and 21.46° and 28.13°E). Its total area is 45,216 km². Over 1,500 islands and islets account for 9.2% of the territory. Estonia is a seaside country, and entirely within the drainage area of the Baltic Sea (Figure 1). Its total coastline length, including the mainland and islands and islets, is 3,794 km. The coastline is characterized by numerous bays, peninsulas, and straits between islands. The coastal sea is shallow and full of shoals.

Figure 1. Location of Estonia in Northern Europe

Situated in the northwestern part of the East-European Plain, Estonia is characterized by a flat topography. The average elevation is about 50 m, and the highest point is 318 m above sea level. The country can be divided into two regions: Lower Estonia and Upper Estonia. Upper Estonia comprises the more elevated areas in the central and southern parts, which were not flooded by the sea and ice lakes during early stages of the Holocene epoch. The soils in Upper Estonia are more fertile and the rural population is denser than in Lower Estonia.

Geologically, the country is located on the southern slope of the Baltic Shield, which is undergoing an isostatic land uplift; Estonia is being lifted 2.8 mm/year on the northwestern coast and 1.0 mm/year in the southwest. Only a comparatively small southeastern part of its territory is subsiding slightly. Isostatic land uplift could potentially reduce, but not alleviate, the impact of sea-level rise on the Estonian coast.

Estonia belongs to the Atlantic continental region of the temperate zone. Its territory lies in a transitional belt with the maritime type of climate in the West-Estonian Archipelago and the continental one in eastern Estonia. Therefore, a remarkable spatial variability can be observed within the limits of the country. Summers are moderately warm (mean air temperature in July lies between 16-17°C) and winters are moderately cold (mean air temperature in February lies between -3.5°C and - 7.5°C). In autumn and winter, coastal regions are much warmer than inland.

The climate of Estonia is humid because precipitation exceeds evapotranspiration. Nevertheless, there are often droughts during summer period. Mean annual precipitation ranges from 550 mm to 750 mm. Stronger rainfalls occur during the period from July to November. It must be emphasized that the precipitation in Estonia has a high temporal variability; variation coefficients of monthly values being over 0.50.

Mean annual total of solar radiation in Estonia is 1.300-1.400 W/m². Due to a very intense cyclonic activity in Northern Europe, the mean wind speed is comparatively high - 5-7 m/s in the coastal zone.

The forests of Estonia belong to a zone of mixed and coniferous forests with relatively favorable growth conditions and good diversity. The variability brought about by natural conditions (parent material of soil, relief, climatic differences) is increased by the fact that the majority of the forests of Estonia have been affected by human activities in various degrees and ways (cutting, drainage, fires etc.).

Today 47.6% of the country, approximately 2.02 million ha, is covered with forest (Statistical Office, 1995). The total area of stands is 1.82 million ha, and there are 53.500 ha of young cultivated forests and forest nurseries. Forests with conifers as the dominant tree species make up 63% of the total forest and 66% of total forest yield; forests with deciduous trees as dominant species constitute 37% of the forest and 34% of the forest yield. Forestry and the forest industry have been and still are important contributions to the economy and employment of Estonia, constituting, together with agriculture 11% of the labor force and 10% of GDP (Statistical Office, 1995).

The peatland area of Estonia is approximately 10.000 km², or 22% of the territory (partly coinciding with forest areas).

Estonia is one of the smallest and least populated countries of Europe - its total population is 1.574.955 inhabitants (1990 Census). The population density is 35 inhabitants/km². About 71% live in urban areas, and 51% live in five largest cities: Tallinn (484.400); Tartu (115.400); Narva (82.300); Kohtla-Järve (76.800); and Pärnu (54.200).

Although small in area, Estonia is relatively rich in natural resources, both mineral and biological, which have been the basis of the economy, and particularly of industry. The most important natural resource is oil shale. Other natural resources worth mentioning include phosphorite, dolomite, sand, gravel, peat, curative mud, and mineral water. The main industrial sector in Estonia is energy. Both the energy and chemical industries are based on oil shale.

2

Estonian agriculture specializes in livestock breeding, which provides 65% to 70% of agricultural production. When Estonia was part of the Soviet Union, agricultural production was based on state and collective farms. Animal husbandry was strongly dependent on imported fodder, and preference was given to pig husbandry and pork production. Most of the meat and dairy products were exported to the other republics of the Soviet Union.

Since the transition process began, the former state and collective farms have been replaced by private farms, which today number over 14.000. The end of state and collective farms, the development of private farms, the loss of previous market, and high prices for fuel and fertilizers are the primary agents affecting the agricultural sector today. A decrease in farmed land (from 1.12 million ha in 1990 to 925.4 thousand ha in 1995) as well as in the number of cattle (1.9 times) is evidence of the changes in the sector. The projection for 1996 is for further decrease in sowed area, but yield quality and the main animal husbandry products, should increase from the 1990-1991 level.

The most important sectors for the vulnerability and adaptation assessment for Estonia are agriculture, forests, and coastal resources. Many other sectors, such as marine ecosystems, water resources, grasslands and livestock, human settlements, are also important, and are integrated with the sectors of primary focus.

The main objective of the vulnerability and adaptation assessment for Estonia is to evaluate climate change and sea level rise impacts on natural systems and human activities and to evaluate possible adaptation options. Thus ecosystems that are most vulnerable to changing

climatic conditions were selected. Three meteorological observation stations in different locations of Estonia were chosen for developing climate change scenarios. Four agricultural experiment stations were selected. Five different (inland and coastal) study areas were selected in the forestry sector. Three rivers with different hydrological regimes were selected in the water resources sector, and five study areas with different geomorphic shore types were selected to assess the effects of accelerated sea level rise on coastal resources.

A number of paleogeographical research work have been done in Estonia, and several projects are going on with general aim of making reconstructions of former climatic conditions and prognosis for the future. That is why historical analogues for developing climate change scenarios have been applied in the current report. Paleogeographical reconstructions give a good possibility to justify the future scenarios.

Figure 2. Map of Estonia's Study Sites

- ▲ Meteorological Observation Stations: 1 - Tõravere; 2 - Võru; 3 - Kuusiku; 4 - Sõrve
- ▽ Agricultural Experimental Stations: I - Eerika; II - Antsla; III - Olustvere; IV - Kuusiku
- Forestry Study Sites: a - Tudu; b - Virtsu; c - Risti; d - Võhma, e - Kärevere
- ☒ Coastal Study Areas: A - Hiiumaa; B - Pärnu-Ikla; C - Matsalu Bay; D - Tallinn; E - Narva-Jõesuu - Kõrval

SCENARIOS USED IN THE V&A ASSESSMENT

Baseline Climate Scenario

The 30-year period (1951-1980) recommended for baseline climate scenarios is sufficiently long to provide a good representation of climate statistics. The World Meteorological Organisation (WMO) also uses a standard 30-year period (1961-1990), but the period 1951-1980 is usually considered preferable because some global warming was observed during the 1980s. Nevertheless, 1961-1990 was chosen for developing baseline climate scenarios for Estonia because of concerns about the quality of data for Estonia from the 1950s. The later baseline period also allows to use of high quality solar radiation data measured at the Tõravere actinometrical station.

The baseline scenario was developed from spatial mean values of monthly temperature, precipitation, and solar radiation measured at meteorological stations in Estonia and averaged for 1961-1990. Mean temperature was calculated for 25 stations. Spatial mean totals of precipitation were found by interpolating average values into grid points using data recorded at more than 100 precipitation stations. We also have a technique that allows us to calculate spatial mean precipitation for smaller regions in Estonia, for example, for river basins. Solar radiation was measured only in Tõravere.

Despite the comparatively small territory, climatic conditions across Estonia are very different. For instance, the monthly mean temperature in January varies from -2.5°C at Vilsandi, the westernmost island of Estonia in the Baltic Sea, to -7.6°C in eastern Estonia.

Therefore, temperature was analyzed using not only spatial mean values but also the values measured at the three stations in different locations (Figure 2). Võru (58°N, 27°E) is situated in southeastern Estonia between two uplands; it has the most continental climate. Kuusiku (59°N, 25°E) lies in the plain in western Estonia, and Sõrve (58°N, 22°E) is located in the southwestern point of Saaremaa Island, with the most maritime climate.

The grid points where the GCM results were calculated usually did not lie within the territory of Estonia, so it was necessary to apply spatial interpolation. In this study, the GCM results (air temperature, precipitation) are interpolated for the center of Estonia, and also for the above-mentioned three stations as well as Tõravere (solar radiation). The GCMs were chosen through comparisons between observed and calculated values.

GCM Climate Change Scenarios

Five GCM outputs were evaluated to determine which model provided the best results for Estonia: the Canadian Climate Centre Model (CCCM), the Goddard Institute for Space Studies (GISS) model, the United Kingdom Meteorological Office (UK89) model, and the Geophysical Fluid Dynamic Laboratory (GFDL30) equilibrium run and GFDL transient model. These outputs were combined with the baseline climate data to produce climate change scenarios that could serve as inputs for vulnerability assessments.

No one GCM describes current climatic conditions in Estonia sufficiently. The results of the model runs for precipitation are highly variable. Four models were chosen for

V&A assessment in Estonia (GISS, CCCM, GFDL30, GFDL transient). One model (UK89) was not used because of excessively low values of mean air temperature, particularly in winter.

General circulation models are the best sources for developing climate change scenarios. The GCM climate change scenarios are developed by adding the difference between $2\times\text{CO}_2$ and $1\times\text{CO}_2$ scenarios to observed values (for temperature) and by multiplying the ratios of $2\times\text{CO}_2$ and $1\times\text{CO}_2$ scenarios by the observed values (for precipitation and solar radiation).

The adjustment statistics of the difference between the equilibrium GCM outputs for monthly mean air temperature and precipitation are presented in Tables 1 a-b. All the values are interpolated for the Türi meteorological station ($58^{\circ}49'\text{N}$, $25^{\circ}25'\text{E}$) which is located in the center of Estonia. The data can be used as a spatial mean estimates.

Table 1 a. Adjustment Statistics for the Difference Between $2\times\text{CO}_2$ and Current ($1\times\text{CO}_2$) Generated by the GISS General Circulation Model

	<i>Jan</i>	<i>Feb</i>	<i>Mar</i>	<i>Apr</i>	<i>May</i>	<i>Jun</i>	<i>Jul</i>	<i>Aug</i>	<i>Sep</i>	<i>Oct</i>	<i>Nov</i>	<i>Dec</i>	<i>Year</i>
Tem per.	6.5	5.6	4.8	4.2	3.8	1.5	1.2	1.0	3.4	3.6	5.2	5.5	3.9
Prec ratio	1.18	1.37	1.35	1.48	1.45	1.07	1.88	1.43	1.27	1.32	1.28	1.13	1.35

Table 1 b. Adjustment Statistics for the Difference Between 2XCO₂ and Current (1XCO₂) Generated by the CCCM General Circulation Model

	<i>Jan</i>	<i>Feb</i>	<i>Mar</i>	<i>Apr</i>	<i>May</i>	<i>Jun</i>	<i>Jul</i>	<i>Aug</i>	<i>Sep</i>	<i>Oct</i>	<i>Nov</i>	<i>Dec</i>	<i>Year</i>
Tem per.	6.5	6.4	5.8	4.9	3.1	3.0	3.1	3.3	2.9	3.3	2.9	3.9	4.1
Prec ratio	1.12	1.33	1.39	1.42	1.09	1.00	0.79	1.20	0.97	1.14	1.29	1.39	1.18

Table 1 c. Adjustment Statistics for the Difference Between 2XCO₂ and Current (1XCO₂) Generated by the GFDL30 General Circulation Model

	<i>Jan</i>	<i>Feb</i>	<i>Mar</i>	<i>Apr</i>	<i>May</i>	<i>Jun</i>	<i>Jul</i>	<i>Aug</i>	<i>Sep</i>	<i>Oct</i>	<i>Nov</i>	<i>Dec</i>	<i>Year</i>
Tem per.	4.9	4.0	5.8	6.5	5.4	4.2	5.0	4.0	2.9	3.8	7.0	6.9	5.0
Prec ratio	0.96	1.17	1.08	1.50	1.41	1.04	1.00	0.95	1.38	1.25	1.36	1.30	1.20

All the scenarios show an increase of temperature of 1° to 7°C. As a rule, warming should be stronger during the cold half of the year. The climate change scenarios for precipitation are highly variable. In most cases, increased precipitation is expected.

The results of the GFDL transient model are presented in Table 2. Adjustment statistics are calculated for the fourth (2000), seventh (2030), and tenth decades (2070) of the transient period. It can be noticed that, as the increase in air temperature is gradual, the most substantial increase in precipitation should take place at the end of the period.

In conclusion, it can be said that the GCM climate change scenarios estimate a general increase in temperature in Estonia, and that winter warming is more substantial than summer warming. They also predict an increase in precipitation, but single model results are quite different. The transient scenario shows that the main increase in precipitation will take place at the end of the transient period, in 2070.

Table 2. Transient Scenario Using Adjustment Statistics from the GFDL Transient General Circulation Model and Daily Weather Data from 1961-1990

	Fourth decade (2000)		Seventh decade (2030)		Tenth decade (2070)	
	Temperatur	Precip. ratio	Temperatur	Precip. ratio	Temperatur	Precip. ratio
January	1.6	0.98	3.6	1.16	6.4	1.23
February	2.3	0.98	2.9	1.05	3.0	1.16
March	2.9	1.19	3.9	1.25	4.4	1.15
April	1.9	0.82	3.1	0.82	3.7	0.91
May	0.8	1.14	3.0	1.05	3.5	1.03
June	-0.7	1.27	1.5	0.91	2.6	1.52
July	-0.6	0.74	2.1	0.76	3.6	1.15
August	0.5	1.01	2.5	0.93	4.1	1.10
September	1.2	1.12	2.9	1.19	4.2	1.35
October	2.8	1.07	3.3	1.11	4.8	1.28
November	1.1	0.88	3.3	0.97	4.7	1.11
December	1.2	1.17	5.7	1.25	6.9	1.44
Annual	1.2	1.03	3.2	1.04	4.3	1.20

Incremental Scenarios

Developing incremental scenarios is the simplest way to obtain climate change scenarios. They provide a wide range of potential regional climate changes and help identify sensitivities to changes in temperature and precipitation. For Estonia, increases in temperature (+2°C, +4°C, +6°C) were combined with no change, and with ±10 % and ±20 % changes in precipitation. As a result, 15 incremental climate change scenarios were developed.

The main disadvantage of using incremental scenarios is that they may not be physically plausible. Also, uniform climate changes throughout a year are not realistic. For instance, in higher latitudes (between 57°N and 60°N), including Estonia, estimated warming in winter should be much greater than in summer. Despite these concerns, incremental scenarios are feasible for Estonia, which has great variability in precipitation; warm and rainy years as well as hot and dry years have occurred.

Baseline Scenario of Population and GNP Growth

**Table 3 a. Baseline Growth in GNP for Estonia.
Average Annual Percentage Growth**

1990-2000	3.0%
2000-2025	3.5%

GNP (billions)

1990	\$5.700
2025	\$23.578

**Table 3 b. Baseline Growth in Population for Estonia.
Average Annual Percentage Growth**

1990-1994	- 4.8%
1994-2000	0 %
2000-2010	- 0.3%
2010-2030	- 7.9%

Population (millions)

1990	1.58
2030	1.38

Sea Level Rise Scenarios

A 1.0 m sea level rise scenario in 2075 was selected for the coastal resources vulnerability and adaptation assessment. A 0.3 m scenario would not have a noticeable effect because of the isostatic land uplift.

Paleoecological Approaches

Paleoecological approaches are widely used for studying environments in the past and for compiling predictions for the future (Chambers, 1993). The main principle of this approach is simple: on the basis of paleoecological data, the state of ecosystems in different time spans in the past can be used ~~these~~ to assess the state of climatic conditions in the future.

Methods

Many paleoecological models and approaches have been developed to reconstruct past environments using sequences of sediments such as peat, lacustrine deposits and ice cores (Berglund, 1986). Naturally, the reconstruction of paleoecological conditions is highly complicated. The formal use of classical principles of actualism has often led to simplified and even wrong conclusions. The environmental variability of the ecosystems in space and time, their tolerance and their inertia often aggravates the problem (Delcourt and Delcourt, 1988). When we look at human-induced changes (such as greenhouse gas warming) in the environment, the intensity of impact over time must also be considered (Punning, 1994).

Paleoecologists have often used intuitive methods to reconstruct paleoclimates from biological data. Multivariate statistical methods developed during the last two decades provide the most powerful approach. These methods are based on several hypotheses: (1) climate is the ultimate cause of changes in the paleobotanical data; (2) the ecology

of the species considered has not varied between the period analysed and the present time, and consequently the relationship between the species and the climate has been constant in time; and (3) modern observations contain all the information needed for interpreting fossil data (Birks, 1981).

Using pollen data and the transfer function method, Huntley and Prentice (1988) have reconstructed mean July temperatures across Europe 6.000 years ago. Palynological (science dealing with pollen) data from Estonia were well represented in this model. In addition, several other methods have been used to reconstruct paleoclimatic parameters. For example, Klimanov (1987) used an information statistical method based on correlation of subrecent pollen spectra with present climatic conditions. Variations in the stable isotopes of oxygen also offer certain possibilities for paleoclimatic reconstructions. The isotopic composition of lake lime is mainly determined by temperature, which has a direct influence on the kinetics of the equilibrium reaction between the carbonate ion and water, as well as by the isotopic composition of water, which in its turn is determined by the isotopic composition of atmospheric precipitation and the intensity of evaporation.

The main outlines of the dynamics of hydrothermic parameters in the northern and northeastern parts of Europe during the last 10.000 years have been reconstructed using results from investigations of glaciers and lake-marl isotopic-geochemical studies (Punning et al., 1984), determinations of macrofossil and pollen distributions in bog and lacustrine sediments (Klimanov et al., 1986; Koff, 1992), and the analysis of data published in many papers (Prentice, 1983; Punning & Raukas, 1985).

Analysis of Estonia

Climate

Generalised data permit the reconstruction of the main tendencies, and in a first approximation even to estimate absolute values of yearly temperatures from 10.000 years ago. The most widely used approach for the reconstruction of long-term climatic change based on palynological data uses the transfer function method (Huntley and Prentice, 1988). The generalised data show that in the beginning of this period the yearly temperatures were up to 4°C lower than the present ones, but about 9.000 years ago, all of northern Europe experienced a rapid increase in annual temperatures.

The time interval between 7.000 and 5.000 years ago is known as the Holocene "climatic optimum". During this time, the summer temperatures in the Northern Hemisphere were, depending on latitude, about 1° to 4°C higher than today. According to Huntley and Prentice (1988) the mean annual temperature gradient in Europe trends north-south, paralleling the gradient of annual insolation. Therefore the differences between reconstructed and present summer and winter temperatures have strong regional variations. It is estimated that in Estonia the summer temperature was about 2.4 °C higher during the climatic optimum than the current summer temperature.

According to current climate models, one of the effects of climate change due to increased greenhouse gas concentrations might be temperatures 2° to 4°C higher than today. Thus, we could consider the reconstructed state of ecological conditions during the Holocene climatic optimum as an analogue of the effects of a 2°C warming.

scenario. This assumes that the general atmospheric mechanisms at the time being considered were the same as today.

Reconstructed precipitation maps for 6.000 years ago show great variability. Guiot et al. (1993) show that in the region of mixed deciduous boreal forest, the precipitation anomalies compared with contemporary numbers were -100 mm to +100 mm. According to Jelovicheva et al. (1988), the anomaly was about +50mm.

Forest Vegetation

In Estonia 6.000 years ago, the dominant vegetation formations were species-rich broad-leaved forests, growing on the Pandivere, Otepää, and Sakala uplands (Figure 3). Here, the dominant species was elm, however oak, lime, maple, ash, birch, and pine were also represented.

Figure 3. Schematic Vegetation Maps Comparing 6.000 Years Ago to Present

1 - Broad-Leaved Forest; 2 - Pine Forest on Dry Sandy Soil; 3 - Alvar Forest; 4 - Spruce Forest; 5 - Swampy Forest; 6 - Area of Inundation

According to this analysis forests dominated by spruce were found only in southeastern Estonia. On the sandy soils of the coast were pine forests. The warmer and wetter climate increased the creation of marshes or fens. Large areas of the northeastern and central part of the country were covered by mire vegetation and swamp forests, where birch and alder dominated in the canopy. On the thin soils of the limestone plateaus of north and west Estonia, alvar forests of oak and pine covered wide areas. "Alvar" is a dry, calciphilous meadow on a limestone plateau; forests growing in these areas are called alvar forests. They are found only in Sweden and Estonia.

Comparison of the estimated structure of the Estonian forest in the warmest period of Holocene with that of today (Laasimer, 1965; Valk and Eilart, 1974; Lõhmus, 1984; Kalda, 1995) indicates that the primary difference is a decrease in broad-leaved forests. Today they are found only in western Estonia. Human activities and changes in climate contributed to the change to species-poor forests. The dominance of spruce has been achieved by silvicultural methods. Hardwood forests of oak, elm, and lime are found only in small groves. Alvar forests have been preserved only locally, and today consist mainly of spruce and pine. The distribution of dry pine forests is related to the poorest sandy soils, and they usually develop as a result of forest fires (Kask and Laasimer, 1975). The swamp forests and mire vegetation have remained largely unchanged.

Sea Level Rise

The wide spectrum of coastal formations at different altitudes, remnants of subfossil fauna, and buried lagoon and lacustrine sediments demonstrate the complicated history of the Baltic. Based on the results of geochronological, biostratigraphical, and geomorphological research, the eustatic sea level curve for the Baltic Sea has been reconstructed and used for characterizing the history of the Baltic Sea (Punning, 1993). The data obtained show that in the beginning of the second half of Holocene, about 6,000 to 5,000 years ago, the ocean level reached its maximum height. The maximum value of the eustatic sea level was 2.0 m above today's level (Punning, 1987).

Depending on the neotectonic uplift of one or another region, the relative extent of sea level changes was and will be quite different. Using the formula:

$$dS = dE/dT,$$

where, dS = flooded area, dE = rate of water sea level rise, and dT = rate of neotectonic uplift, it is possible to calculate the spatial extent of sea level rise.

In western Estonia we find ancient coastal formations of different ages tens of kilometers from the present shore. These formations, as well as lagoon and bog deposits covered by sediments, permit the reconstruction of the extent of the sea about 7.000 to 5.000 years ago (Kessel and Punning, 1984). Because of the high sea level and durable hydrological connection between the ocean and the Baltic Sea, the salinity of the Gulf of Finland reached 11-12 ppt (today it is 5-7 ppt) and such molluscs as *Littorina littorea*, *L. saxatilis*, and *Zippora membranacea* were widespread.

Discussion

Therefore, in principle, it is possible to find the past analogous situations to those predicted as the result of GHG warming. The use of paleoecological reconstructions for these periods could provide very valuable information for understanding the state of the environment in the future. At the same time, there are many factors that will hinder the direct use of paleoecological data. In the interpretation of paleodata and comparison with future situations, one must take into account such complications as similarity of natural conditions, cause-consequence adequacy, stability of hierarchic correspondence of allogenic factors, and intensity in time.

ESTONIA'S V & A ASSESSMENT FOR THE AGRICULTURE SECTOR

Introduction

Estonian agriculture specializes in animal husbandry, which depends on the yields of crops. Because meteorological conditions in Estonia during the growth periods of plants vary substantially from year to year, the yields of crops and grasslands are quite unstable, differing sometimes as much as threefold (Table 4).

Table 4. Yields of Different Crops Depending on Weather Conditions.

Crops	Probability (%)				
	10	30	50	70	90
	Yields (t/ha)				
Barley	5.8	5.1	4.6	4.0	2.8
Oats	5.6	4.7	4.0	3.2	2.2
Summer Wheat	5.6	4.8	4.4	3.7	2.9
Rye	5.1	4.1	3.6	3.1	1.9
Winter Wheat	5.1	4.1	3.5	3.0	2.8
Potatoes	34.7	27.7	23.0	19.3	14.2
Grass / Clover Mixture	10.0	8.9	8.3	6.7	5.7

Despite a small territory, the soil and climate conditions for plants growth are extremely variable in Estonia. For example, in central Estonia the pedoclimatic conditions for cultivation of cereal are 20-30% more favourable than in northern and southeastern parts of the country (Figure 4).

Figure 4. Relative Suitability of Pedoclimatic Conditions for Cultivation of Cereal without Using Fertilizers

Methods Used for the V&A Assessment

Crop Models Used in the Assessment

Of the total arable land in Estonia, 55% is covered by grasslands and 38% by grain fields. The main cereal is barley (60% of the planted field devoted to cereal). Consequently, the vulnerability and adaptation assessment for the agriculture sector in Estonia has focused on the analysis of possible changes in yields of barley under different climate change scenarios. This assessment also considers the impact of climate change on potato and clover-timothy mixture yields.

The CERES-Barley model (Richie et al., 1989) was used for Estonia's crop productivity assessment. Although theoretical and agronomical aspects of the crops productivity in Estonia have been examined for a long time (Sau and Viiralt, 1974; Ross, 1975; Tooming, 1977; and Older et al., 1994), the above mentioned models as well as GCMs were used for the vulnerability and adaptation assessment for the first time.

For analysis of sensitivity of barley yields to temperature, precipitation, and carbon dioxide level, incremental scenarios were created, combining certain changes in the climatic variables (-2°, -1°, 0°, +1°, +2°, +4°, and +6°C in temperature; 0%, ±10%, and ±20% in precipitation; and 330 ppm, 355 ppm, 440 ppm, and 580 ppm in CO₂ level).

Using the model, it was possible to simulate the plant development and the yield capacity, integrating the climatic, soil, genotype, and management factors.

Calibrating the models, it appeared that the CERES-Barley model was more appropriate to dry sandy and rubbly soils. Correlation coefficients between model-predicted and the yields, measured in the field experiments on sandy Haplic Podzols, were 0.42 to 0.78. On Gleysols and on soils with heavy texture the correlations were less significant. It is explained by a great variation of groundwater level and water supply in the beginning of the vegetation period, which is strongly dependent on the preceding winter weather conditions. Unfortunately, the CERES-Barley model doesn't take it into account.

In addition to barley, possible changes in potato (main food crop in Estonia) yields were also examined using the results of our earlier experiments. Primarily, it was planned to evaluate the effect of climate change on the productivity of herbage using the SPUR-2 model. Calibrations of the model didn't give reliable results, particularly in wet areas where grasslands in Estonia predominate. Therefore, the analysis of timothy-clover mixture was done using our own biophysical models.

Two GCMs : (1) the Canadian Climate Centre Model (CCCM), and (2) the Geophysical Fluid Dynamics Laboratory equilibrium run (GFD3) model were used studying the climate change effects (Table 5). The 22-year period (1966-1987) was taken for baseline climate scenarios, coinciding with the period of the barley field trials at the experimental stations (Figure 5).

Table 5. Baseline and Predicted by the CCCM and GFD3 Models Climatic Variables at the Study Sites

Climatic Variables	Month	Antsla			Olustvere			Kuusiku		
		Base line	CCC M	GFD 3	Base line	CCC M	GFD3	Base line	CCC M	GFD 3
Temperature (°C)	April	4.6	9.9	10.9	4.3	9.2	10.7	3.6	8.3	10.1
	May	11.5	14.1	16.7	11.2	14.2	16.5	10.2	13.5	15.6
	June	15.3	18.0	19.3	15.1	18.0	19.3	14.1	17.2	18.4
	July	17.0	20.0	21.9	16.8	19.9	21.8	15.8	19.0	20.8
	Aug.	16.1	19.4	20.0	15.9	19.2	19.9	15.1	18.4	19.1
	Sept.	11.0	13.8	13.6	10.8	13.7	13.6	10.2	13.2	13.2
Total Precipitation (mm/Month)	April	40	59	59	38	54	56	41	56	62
	May	50	52	74	52	56	75	46	50	63
	June	63	66	62	68	68	69	56	54	58
	July	76	58		79	61	81	81	64	81
	Aug.	81	91	83	82	98	80	78	95	74
	Sept.	72	68	82 108	79	76	112	89	87	119
Solar Radiation (MJ/m ² /Day)	April	11.8	11.0	9.4	12.2	11.3	9.4	12.1	11.4	9.6
	May	17.5	17.0	15.8	17.8	17.3	17.1	18.0	17.5	18.2
	June	20.4	20.2	22.2	20.7	20.7	21.9	21.0	21.0	22.3
	July	18.8	18.4	19.7	19.0	18.8	19.6	18.9	18.9	19.3
	Aug.	15.3	14.7	16.1	15.1	14.5	15.7	14.8	14.2	15.3
	Sept.	8.6	8.6	8.4	8.7	8.7	8.5	8.5	8.3	8.2

Figure 5. Baseline Daily Average Solar Radiation and Precipitation of the Period May 1 - Aug. 31 at the Experimental Stations.

Selection of Study Sites

Three case study areas - Antsla, Olustvere, and Kuusiku (Figure 2) - were selected in different parts of Estonia. All three areas have experimental stations where special long-term trials (1966-1987) have been carried out. Four most characteristic soil types of Estonia of different texture and properties were chosen for the analysis. The soils in the FAO (1994) system are the following: (1) Haplic Podzol in Antsla; (2)

Podzoluvisol in Olustvere; (3) Cambi-Rendzic Leptosol; and (4) Basesaturated Gleysol in Kuusiku.

Haplic Podzols and Podzoluvisols occur in southern Estonia on noncalcareous sandy and loamy till. They are acid and poor in nutrients and humus, occypying 3.3% of the arable land of Estonia. Cambi-Rendzic Leptosols on pebble till are rich in humus and carbonates, but very dry. They are typical to northern and western Estonia, providing about 10% of the arable land. Gleysols (17% of the arable land) prevail on the West-Estonian Lowland. Some physical and agrochemical properties of the above listed soils are given in Table 6.

The data on the barley field trials were collected from the Estonian Research Institute of Agriculture. The trials consist of 6-field crop rotations: potato → barley → barley → timothy-clover mixture → timothy-clover mixture → rye.

The data on barley are based on 16 variants of fertilizing experiments. The variants are the following: (1) $N_0P_0K_0$; (2) N_{35} ; (3) $N_{35}P_{8.7}$; (4) $N_{35}P_{8.7}K_{24.9}$; (5) $N_{70}P_{8.7}K_{24.9}$; (6) $N_{70}P_{8.7}K_{49.8}$; (7) $N_{70}P_{17.5}K_{24.9}$; (8) $N_{70}P_{17.5}K_{49.8}$; (9) $N_{105}P_{17.5}K_{49.8}$; (10) $N_{105}P_{17.5}K_{74.7}$; (11) $N_{105}P_{26.2}K_{74.7}$; (12) $N_{140}P_{26.2}K_{74.7}$; (13) $N_{70}P_{17.5}K_{49.8}$ + manure (60 t/ha); (14) $N_{105}P_{17.5}K_{49.8}$ + manure (60 t/ha); (15) $N_{70}P_{17.5}K_{49.8}$ + manure (90 t/ha); (16) $N_{105}P_{17.5}K_{49.8}$ + manure (90 t/ha).

Table 6. Some Physical and Agrochemical Properties of Soils at the Study Sites

Experimental station, soil	Texture	Soil depth cm	Lower limit cm ³ /cm ³	Upper limit cm ³ /cm ³	Saturated soil water cm ³ /cm ³	Bulk density g/cm ³	pH _{KCl}	C %
<u>Antsla</u> Haplic Podzol	loamy sand/sand	10	0.046	0.203	0.454	1.40	5.1	0.87
		20	0.059	0.190	0.444	1.51	5.1	0.75
		30	0.059	0.167	0.439	1.52	5.1	0.75
		40	0.062	0.170	0.414	1.60	-99	0.41
		50	0.057	0.134	0.440	1.59	-99	0.23
		60	0.054	0.112	0.425	1.54	-99	0.17
		70	0.028	0.111	0.419	1.54	-99	0.12
		80	0.045	0.138	0.431	1.55	-99	0.12
		90	0.043	0.138	0.419	1.60	-99	0.12
		100	0.036	0.105	0.424	1.57	-99	0.12
<u>Olustvere</u> Podzoluvizol	sandy loam/sandy clay loam	10	0.079	0.304	0.489	1.40	4.6	0.93
		20	0.056	0.322	0.429	1.55	4.6	0.81
		30	0.041	0.324	0.415	1.59	4.6	0.29
		40	0.07	0.301	0.419	1.60	-99	0.17
		50	0.151	0.289	0.422	1.65	-99	0.17
		60	0.122	0.266	0.421	1.63	-99	0.12
		70	0.115	0.278	0.379	1.74	-99	0.12
		80	0.077	0.274	0.384	1.70	-99	0.12
		90	0.061	0.262	0.377	1.70	-99	0.12
		100	0.025	0.152	0.388	1.65	-99	0.12
<u>Kuusiku</u> Cambic Rendzic Leptosol	rubbly loamy sand	10	0.104	0.271	0.446	1.41	6.6	1.62
		20	0.104	0.267	0.439	1.40	6.6	1.57
		30	0.096	0.244	0.41	1.55	6.6	0.64
		40	0.103	0.236	0.382	1.64	-99	0.58
		50	0.05	0.225	0.377	1.67	-99	0.17
		60	0.04	0.192	0.354	1.70	-99	0.17
		70	0.038	0.185	0.357	1.75	-99	0.12
		80	0.036	0.184	0.357	1.75	-99	0.12
		90	0.034	0.158	0.357	1.75	-99	0.12
		100	0.032	0.158	0.357	1.75	-99	0.12
<u>Kuusiku</u> Base-saturated Gleysol	loamy sand/sand	10	0.094	0.519	0.651	0.90	6.4	5.74
		20	0.104	0.541	0.649	0.90	6.4	5.92
		30	0.058	0.245	0.551	1.15	6.4	1.33
		40	0.022	0.139	0.517	1.30	-99	0.6
		50	0.022	0.139	0.440	1.54	-99	0.6
		60	0.017	0.145	0.441	1.53	-99	0.6
		70	0.019	0.097	0.410	1.56	-99	0.6
		80	0.026	0.111	0.442	1.53	-99	0
		90	0.032	0.130	0.445	1.52	-99	0
		100	0.013	0.105	0.443	1.49	-99	0

Results of the V&A Assessment

Barley

The results of the vulnerability and adaptation analysis on barley using the CERES-Barley model are presented as weighted average yields on different soils in different locations of Estonia (Figures 6, 7, 8, and 9; Tables 7, 8, and 9). The simulations done with a barley cultivar "Julia" indicate a considerable decrease in productivity in the case of climate warming. At the present carbon dioxide concentration level, the increase in temperature without changes in precipitation would decrease the barley yield by 45-48% on unfertilized soils. On arid fertilized sandy soils, the temperature rise of 6°C would cause the drop of barley productivity by even 56-61%. On gleyic and gleyed soils with heavy texture and much better water supply the effect of higher temperatures is less notable. Consequently, the properties of soils and their location are very important factors in climate change impact assessment on the productivity of crops (Table 10). Physiological effects of CO₂ are less evident than the effects of temperature and precipitation.

On dry sandy soils barley yields mainly depend on the rate of nitrogen fertilization and the plant water supply. On the other soils the relative effect of fertilization is less important. For instance, due to climate change, the weighted mean yield on unfertilized soils decreases by 0.41 t/ha, making up 18.8% of the total yield. After using nitrogen fertilizer, the yield drops by 1.07 t/ha, i.e. 17.8% of the fertilized total yield respectively.

Figure 6. Sensitivity of Barley Yield to Climate Change on Haplic Podzols (% of the Base Yield)

Figure 7. Sensitivity of Barley Yield to Climate Change on Podzoluvisols

Figure 8. Sensitivity of Barley Yield to Climate Change on Cambi-Rendzic Leptosols

Figure 9. Sensitivity of Barley Yield to Climate Change on Base-saturated Gleysols

Table 7. Relative Decrease (%) of Simulated Yields of the Barley Cultivar 'Julia' Depending on Temperature Rise

Soil	Temp diff. °C	Whithout Fertilizing						With Nitrogen Fertilizing (70 kg /ha)					
		Precipitation, %						Precipitation, %					
		-20%		0%		+20%		-20%		0%		+20%	
		330 pp m	580 pp m	330 pp m	580 pp m	330 pp m	580 pp m	330 pp m	580 pp m	330 pp m	580 pp m	330 pp m	580 pp m
Haplic Podzol	+2	14	13	8	8	8	5	24	24	26	23	25	21
	+4	37	35	38	32	26	26	45	45	49	46	50	44
	+6	50	47	48	42	42	33	58	59	61	60	61	58
Podzoluvisol	+2	16	10	16	11	14	10	24	15	23	13	20	12
	+4	30	21	30	20	27	19	41	32	39	28	36	26
	+6	39	28	38	26	36	24	55	47	53	43	51	40
Cambi-Rendzic Leptosol	+2	19	11	17	11	16	11	26	18	24	14	21	10
	+4	35	29	34	27	30	26	41	35	41	31	39	28
	+6	48	40	45	36	41	33	56	51	57	49	56	46
Gleysol	+2	19	16	3	1	17	17	30	23	23	18	24	20
	+4	1	+2	6	3	18	16	28	27	23	21	23	16
	+6	0	+2	10	5	19	16	35	30	41	34	39	30

It is necessary to consider the biological peculiarities of different cultivars. Their sensitivity to climate change is largely variable (Table 11). The differences in barley yields due to different cultivars make up 0.4-0.9 t/ha.

Table 8. Sensitivity of the Barley Cultivar "Julia" Yield (t/ha) to Changes in Temperature, Precipitation, and CO₂ Level (330 ppm and 580 ppm) without Using Fertilizers

Precip. Diff. (%)	Temp. Diff. (°C)	NORTH ESTONIA		WEST ESTONIA		SOUTH ESTONIA	
		330 ppm	580 ppm	330 ppm	580 ppm	330 ppm	580 ppm
0	0	1.38	1.62	1.21	1.42	1.57	1.80
	+2	1.24	1.55	1.15	1.43	1.41	1.70
	+4	1.10	1.38	1.06	1.36	1.23	1.54
	+6	1.00	1.28	1.03	1.29	1.13	1.42
+10	0	1.42	1.73	1.29	1.60	1.62	1.87
	+2	1.27	1.58	1.20	1.50	1.43	1.73
	+4	1.14	1.44	1.15	1.43	1.26	1.56
	+6	1.06	1.34	1.10	1.38	1.17	1.48
+20	0	1.69	2.00	1.71	2.05	1.82	2.09
	+2	1.41	1.71	1.42	1.72	1.53	1.81
	+4	1.31	1.60	1.39	1.70	1.38	1.69
	+6	1.22	1.55	1.35	1.70	1.29	1.63
-10	0	1.34	1.59	1.12	1.35	1.55	1.79
	+2	1.09	1.38	0.91	1.15	1.29	1.56
	+4	0.94	1.19	0.84	1.05	1.11	1.37
	+6	0.82	1.07	0.78	0.98	0.99	1.24
-20	0	1.32	1.58	1.11	1.34	1.54	1.80
	+2	1.06	1.37	0.90	1.13	1.27	1.57
	+4	0.93	1.18	0.83	1.05	1.10	1.37
	+6	0.81	1.06	0.78	0.98	0.99	1.24

Table 9. Sensitivity of the Barley Cultivar "Julia" Yield (t/ha) to Changes in Temperature, Precipitation, and CO₂ Level (330 ppm and 580 ppm) Using Fertilizers (N 70 kg/ha)

Precip. Diff. (%)	Temp. Diff. (°C)	NORTH ESTONIA		WEST ESTONIA		SOUTH ESTONIA	
		330 ppm	580 ppm	330 ppm	580 ppm	330 ppm	580 ppm
0	0	3.57	4.46	3.07	3.78	3.86	4.86
	+2	2.71	3.69	2.37	3.10	2.97	4.08
	+4	2.25	3.16	2.04	2.74	2.41	3.41
	+6	1.81	2.57	1.74	2.39	1.96	2.81
+10	0	3.70	4.66	3.19	4.02	4.00	5.03
	+2	2.88	3.98	2.50	3.36	3.10	4.28
	+4	2.43	3.42	2.24	3.05	2.58	3.65
	+6	2.00	2.86	1.97	2.74	2.13	3.07
+20	0	4.18	5.10	3.86	4.69	4.40	5.42
	+2	3.22	4.32	2.95	3.81	3.42	4.56
	+4	2.73	3.76	2.61	3.49	2.84	3.92
	+6	2.22	3.19	2.28	3.17	2.33	3.34
-10	0	3.48	4.41	3.05	3.76	3.76	4.80
	+2	2.62	3.65	2.34	3.08	2.87	4.01
	+4	2.18	3.10	2.02	2.73	2.33	3.32
	+6	1.77	2.52	1.73	2.37	1.90	2.73
-20	0	3.17	4.19	2.78	3.55	3.48	4.59
	+2	2.29	3.32	1.96	2.75	2.56	3.72
	+4	2.01	2.83	1.83	2.54	2.15	3.14
	+6	1.73	2.46	1.72	2.36	1.83	2.63

Table 10. Effects of the GCM Scenarios on the Barley Cultivar "Julia" Yield at the Study Sites

Climate Scenario	N kg/ha	Antsla, Haplic Podzol		Olustvere, Podzoluvisol		Kuusiku, Cambi-Rendzic Leptosol		Kuusiku, Base-saturated Gleysol	
		Without CO ₂ Effect	With CO ₂ Effect	Without CO ₂ Effect	With CO ₂ Effect	Without CO ₂ Effect	With CO ₂ Effect	Without CO ₂ Effect	With CO ₂ Effect
Baseline	0	1.54	1.95	2.31	2.43	1.73	2.00	1.14	1.36
	70	3.21	4.69	5.44	6.77	4.54	5.85	2.91	3.54
CCCM	0	1.01	1.38	1.73	2.00	1.25	1.53	1.16	1.42
	70	2.04	3.11	3.97	5.54	3.13	4.54	2.35	3.20
GFD3	0	0.97	1.30	1.40	1.71	1.17	1.46	1.71	2.09
	70	1.75	2.69	3.38	4.80	2.73	4.10	3.05	4.03

Table 11. Simulated Yields of the Barley Cultivars "Julia" and "Mona" with Adaption and Fertilization (N 70 kg/ha)

Precip. Diff. (%)	Temp. Diff. (°C)	'JULIA'		'MONA'	
		330 ppm	580 ppm	330 ppm	580 ppm
0	0	3.21	4.69	2.35	3.39
	+2	2.37	3.60	1.67	2.46
	+4	1.64	2.52	1.14	1.75
	+6	1.26	1.88	0.85	1.28
+10	0	3.44	4.87	2.53	3.50
	+2	2.55	3.78	1.77	2.59
	+4	1.74	2.67	1.20	1.83
	+6	1.34	1.99	0.90	1.36
+20	0	3.62	5.02	2.69	3.56
	+2	2.70	3.96	1.87	2.68
	+4	1.82	2.80	1.26	1.91
	+6	1.41	2.10	0.95	1.44
-10	0	2.90	4.39	2.12	3.16
	+2	2.18	3.36	1.55	2.31
	+4	1.53	2.36	1.08	1.65
	+6	1.17	1.76	0.79	1.21
-20	0	2.56	4.02	1.90	2.89
	+2	1.96	3.06	1.40	2.15
	+4	1.40	2.20	1.00	1.56
	+6	1.07	1.64	0.72	1.11

Herbage

The soil and climate conditions for herbage are the most favourable in central Estonia (Calcareous Cambisols and Calcareous Luvisols) and in western Estonia (Gleysols on

Table 12. Relative Suitability of Soil and Climate Conditions (%) in Relation to the Järvamaa District for Cultivation of Barley and Herbage. C-central; E-eastern; N-northern; NW-northwestern; W-western; SW-southwestern; SE-southeastern; S-southern; NE-northeastern

District		Barley		Clover/Timothy Mixture in Field Crop Rotation	
		Without Fertilizers	Amount of Fertilizers N ₉₀ P ₃₉ K ₇₅	Without Fertilizers	Amount of Fertilizers N ₉₀ P ₃₉ K ₇₅
Järvamaa	C	100	100	100	100
Viljandimaa	C	97	99	99	104
Jõgevamaa	C	96	98	100	104
Tartumaa	E	94	96	97	101
Lääne-Virumaa	N	91	95	91	92
Harjumaa	NW	86	91	83	88
Raplamaa	C	86	91	94	94
Pärnumaa	SW	86	91	99	100
Põlvamaa	SE	84	91	93	97
Valgamaa	S	83	90	94	100
Läänemaa	W	82	89	91	92
Ida-Virumaa	NE	81	87	91	94
Võrumaa	SE	79	86	92	97
Hiiumaa	W	76	88	85	86
Saaremaa	W	75	87	82	86

different types of deposits) (Table 12). A temperature rise of 4°C would increase timothy-clover mixture yield by 10%. The productivity of pastures in Estonia depends on solar radiation, temperature and water supply. The productivity of legume-grasses sward can be characterized by the following equation:

$$y = 76.6 - 0.0292 x_1 + \frac{17394}{x_1} + 0.0437 x_2 - 10.6 x_3$$

where y = dry matter yield (in 100 kg/ha); x_1 = total evapotranspiration (May-September in mm); x_2 = sum of temperatures $> 10^{\circ}\text{C}$; x_3 = pasture sward age (in years). Correlation coefficient $R = 0.84$.

It is necessary to irrigate the sown pastures (100-120 mm in average; in some droughty years even up to 200 mm) to get a maximum yield (7-12 t/ha of dry matter). Such irrigation rates may increase the pastures yield by 1.3-1.9 t/ha (Sau, Viiralt, 1974; Older et al., 1994). At the same time, during unfavourable years with cool summers the yield may decrease by 14-34% (Jürisson et al., 1984). In general, the sown pastures productivity depend on the type of grass sward and the rates of fertilization and irrigation (Table 13).

Table 13. The Influence of Nitrogen Fertilization and Irrigation on the Yield of Sown Pastures (Viiralt, 1986)

Grass Sward	N kg/ha	Dry Matter Yields (t/ha)	
		Unirrigated	Irrigated
Grasses	0	1.83	2.56
	100	4.96	6.52
	200	7.63	9.27
	300	8.37	10.58
White Clovergrasses	0	3.03	6.48
	100	5.44	7.09
	200	6.25	9.03

Potato

Potato is very sensitive to climate conditions. In general, it is worth mentioning that high temperatures during planting and sprouting period give a positive effect on potato yield. The relationships between the temperatures after sprouting and during harvesting are less significant. On overmoist gleyed soils, heavy rainfalls in spring cause very strong decrease in potato yield. For instance, every mm of precipitation in spring

reduces the potato yield by 0.3-0.6 t/ha. However, precipitation during and after flowering give a very positive result (Kitse, Roostalu, 1970).

Aggregate Crop Model Results

For the analysis of the effect of various climate change scenarios on the national grain yield, changes in barley productivity were estimated by aggregating the tested soil results, and presenting as weighted mean values over all cultivated area of Estonia. As the tested soils of various properties are typical cultivated soils in the country, the aggregation makes it possible to evaluate reliably the potential effect of climate change on the national grain yield (Table 14). The aggregation analysis was made using the CCCM climate change scenario. Physiological effects of CO₂ concentrations were also considered in the calculations.

Table 14. Aggregation of the CCCM Results for Barley

Soils	Main Occurance	Sowing Area of Barley (thous. ha)	N (kg/ha)	Percent of Total Production	Percent of Change in Yield	Weighted Average
Cambi-Rendzie Leptosols, Calcareous Cambisols and Luvisols	North and Central Estonia	84	0	48.9	-18.4	-0.44
			70	49.6	-18.7	-1.25
Haplic Podzols.Podzoluvisols.Stagnic Luvisols and Planosols	South Estonia	68	0	39.2	-18.9	-0.45
			70	39.1	-19.2	-1.26
Gleysols	West Estonia	36	0	11.9	+ 4.4	+0.04
			70	11.3	- 9.0	-0.34
National		188	0	100	-18.8	-0.41
			70		-17.8	-1.07

Adaptation Options

Using the results of the aggregate crop model, both the CCCM and GFD3 scenarios, and also the earlier crop management experiences, it can be said that main adaptation options for barley in Estonia are: (1) irrigation; (2) nitrogen fertilization; (3) breeding new cultivars; and (4) changing the date of planting (Tables 15 and 16).

Table 15. Effects of GCM Climate Change Scenarios on Barley Yields on Haplic Podzols without Adaptation and CO₂ Influence (change from baseline in percent)

Scenario	N (kg/ha)	Yield (t/ha) GCM Effects (%)		Growth Period Duration	Growth Period Precipitat.	Growth Period Evapotrans	Water Used for Irrigation
		Non- irrigated	Irrigated	(day)	(mm)	(mm)	(mm)
Baseline	0	1.54	1.97	103	247	213	46
	35	2.73	4.30			298	118
	70	3.21	5.48			313	130
	105	3.30	5.79			316	132
	140	3.34	5.88			316	132
CCCM	0	66	72	94	79	84	100
	35	65	73			84	93
	70	64	73			88	97
	105	65	75			90	102
	140	66	77			91	103
GFD3	0	63	62	89	84	77	78
	35	56	58			75	73
	70	55	54			77	82
	105	56	55			78	83
	140	56	55			78	83

It is possible to reduce the negative influence on barley yield by changing the planting date (Figure 10). The difference between the CCCM and the baseline barley yields essentially decreases in optimizing the planting date and irrigating the dry sandy soils. Resulted from climate warming, the optimum planting date arrives 19 days earlier.

Figure 10. Changes in Growth Period Duration of the Barley Cultivars "Mona" and "Julia" on Haplic Podzols, Resulted from Temperature

Different cultivars respond to climate change in different way. Their sensitivity and adaptation ability to new climatic conditions vary substantially (Table 11; Figure 11).

**Table 16. Effects of GCM Climate Change Scenarios on Barley Yields on Haplic Podzols with Adaptation and without CO₂ Influence
(Change from baseline in percent)**

Scenario	N (kg/ha)	Yield (t/ha) GCM Effects (%)		Growth Period Duration	Growth Period Precipitat.	Growth Period Evapotrans	Water Used for Irrigation
		Non- irrigated	Irrigated	(day)	(mm)	(mm)	(mm)
Baseline	0	1.59	1.95	102	242	217	56
	35	2.59	4.10			295	112
	70	2.97	5.35			313	132
	105	3.08	5.72			316	134
	140	3.17	5.83			317	136
CCCM	0	62	61	86	86	77	61
	35	76	73			85	93
	70	74	69			87	92
	105	73	68			88	94
	140	72	68			88	93
GFD3	0	45	43	79	93	68	39
	35	51	45			66	55
	70	49	42			68	55
	105	49	42			69	58
	140	48	42			69	60

Figure 11. Changes in the Barley Cultivars "Mona" and "Julia" Yields on Haplic Podzols under GCM Scenarios Dependent on Fertilization

Discussion

Agriculture is one of the most vulnerable sectors to climate change in Estonia. It is obvious that changing climatic conditions will affect the productivity of different crops. If it really happens, the policy makers have to apply respective adaptation strategies.

Despite the small size of Estonia, the soil and climate conditions are extremely variable and affect suitability for plant growth. Thus, the effects of changes depend foremost on local meteorological conditions and soil properties. As the results of modeling show, in the case of temperature rise the crop yields will decrease everywhere in Estonia. The most vulnerable are the cultivated areas on dry sandy soils. The fields on gleyic and gleyed soils would be less affected. However, on these soils the yield is so low (1.42-3.20 t/ha) and unstable that cultivation of barley is not profitable there (Elmet et al., 1995).

Resulted from higher temperatures, the duration of growth period shortens and the biomass formation of barley decreases. A temperature rise of 6°C shortens the growth period by three weeks, which in its turn decreases the amount of precipitation. On dry sandy soils barley yields mainly depend on the rate of nitrogen fertilization and the plant water supply. On the other soils the relative effect of fertilization is less important. In general, fertilization may increase barley yield as much as threefold.

Earlier experiments using biophysical models for the productivity of various crops indicate that the effect of climate change on herbage cultivation is more favourable than on cereals. The productivity of pastures in Estonia depend on light interception, temperature and water supply. The best conditions for herbage cultivation are in western Estonia.

Potato - the main food crop in Estonia - is very sensitive to climate conditions. Usually, high temperatures during planting and sprouting periods of potato exercise a beneficial effect. Various potato cultivars have different disease - resistance, which, in our conditions, has a great importance to the formation of potato yield. By climate change scenarios, it can be concluded that the potato yield becomes unstable, and it may fall, particularly on unfertile and overmoist soils. Similar findings have been published in the U.S.A. (Rosenzweig et al., 1994). Unlike herbage, the soil and climate preconditions for cultivation of potato in western Estonia are relatively unfavourable.

Introducing adaptation strategies for the agriculture sector, changes in planting date, application of nitrogen fertilizers, irrigation, and breeding of various cultivars would be of great importance.

ESTONIA'S V & A ASSESSMENT FOR THE FORESTRY SECTOR

Potential forests responses to global climate change were examined in five forest stands in different regions of Estonia. In Estonia, there are 87 native and over 500 introduced tree and shrub species (Karoles et al., 1994). The primary tree species are Scots pine (*Pinus sylvestris* L.) which account for 40% of standing volume, Norway spruce (*Picea abies* L. Karst.) which are 26%, and birches (*Betula pendula* Roth., *pubescens* Ehrh.) which are 26%.

The results of the Forest Gap Model calculations indicate that forest trees' competition capacity in particular may change under rising temperature and annual precipitation, with a subsequent increase or decrease in the productivity of species. Generally, computer simulations show that climate warming is reflected by an increase in the productivity of forest stands in the boreal zone (Kellomäki et al., 1988; Kellomäki & Kolström, 1992; Solomon & Leeman, 1990). However, there are also modelling results that show a decrease in total forest biomass under climate change conditions as a result of increased CO₂ in the atmosphere (Overpeck et al., 1990; Pastor & Post, 1988). It has been ascertained that plant communities can respond to changes in climate by changing the competitive advantages between species (Solomon & Cramer, 1993).

Our calculations reflected the strong response of forests to climate warming, revealed in both the composition and age structure of forest stands.

Preliminary Screening

The first step of preliminary screening included the study of the Holdridge (1967) Life Zone Classification Model. Since the computer version of the model was not available, we have only characterized the possibility of the large-scale change of vegetation in the case of climate warming. The occurrence of any Life Zone Class depends on only two variables - annual precipitation and biotemperature. The baseline mean was calculated for the whole territory of Estonia, on the basis of data from 1961-1990. According to these computations, the mean annual precipitation is 663 mm and the mean biotemperature 6.6°C. According to the diagram given by Holdridge, the vegetation of Estonia belongs to the class 'Moist forest'. An increase in the mean temperature of 4° and in precipitation of 10% would result in a mean biotemperature of 9.5°C and a mean annual precipitation of 730 mm. In this case, the major ecosystem complex in Estonia would still be 'Moist forest'. Consequently, there would be no drastic changes in ecosystem structure and species composition.

The results given by Holdridge's diagram are also confirmed by vegetation descriptions. The species composition and structure of forest stands in Estonia have been described by Laasimer (1965) and Lõhmus (1984). Estonia belongs to the so-called boreo-nemoral vegetation zone, which means that both boreal forest types (mainly conifer forests with predominating *Pinus sylvestris* and *Picea abies* on podzols) and nemoral deciduous forests (*Ulmus glabra*, *Acer platanoides*, *Fraxinus excelsior*, *Tilia cordata*, *Quercus robur*) with abundant *Picea abies* (mostly on leptosols, cambisols and luvisols) are represented. Of the predominating tree and shrub species, none is on the southernmost limit of its distribution area. Thus, in the case of

a moderate warming of the climate, the exclusion of some of these species is not expected.

If the mean annual temperature increased by 4°C and the mean annual precipitation by 10%, the climate in the region of Estonia could resemble to that of southern Poland or central Germany. The study of the forest vegetation in analogous regions may help to predict the general trends of community changes. In the above mentioned regions which have edaphic conditions quite similar to Estonia several new tree species appear (Hulten 1950). *Fagus sylvatica*, *Carpinus betulus*, *Quercus petraea* and *Ulmus carpinifolia* occur in abundance and one can also find *Acer campestre* and *Tilia platyphylla*. According to Ellenberg (1982), the most widespread forest community type in these regions is *Fagus sylvatica* forest, especially the central type in mesophyte conditions *Eu-Fagion*. *Carpinus betulus* (*Carpinion*) forest occurs on both relatively dry and relatively moist, moderately fertile soils. Oak forest (*Quercion robur-petraeae*) grows on very acid soils. Another type of oak forest (*Quercion pubescenti-petraeae*) can be met in very xerophilous conditions. In both cases, oak species can grow mixed with pine. In moist and fertile conditions, one can find *Alno-Ulmion*.

In the event of climate warming, the forest communities in Estonia will probably change towards the above mentioned communities. The mixed nemoral forest types could change towards *Fagion* and in less favourable soil conditions towards *Carpinion*. The boreal forest types, which are mostly characteristic of acid and/or very dry soils, would change towards different types of *Quercion*. Consequently, due to the transitional nature of the forest communities (a border between boreal and

nemoral forests) in Estonia, the expected changes in tree stand compositions would be relatively large.

Methods Used for the V&A Assessment

Forest Ecosystem Models Used in the Assessment

In order to determine the responses of Estonian forests to changes in climatic conditions, the simple version of the Forest Gap Model (FGM) (Botkin et al., 1972; Shugart, 1984), recommended by the U.S. Country Studies program, was used. In general, different gap models can be useful tools for predicting successional changes in forest stands and also for planning adaptation strategies. However, the model assumes the uniformity of edaphic conditions and thus does not allow the simulation of forest growth along soil gradients. Also, the model does not incorporate vital factors such as human activity, fires, diseases and synergism between environmental stresses.

We used the Holdridge Life Zones Classification Models (Holdridge, 1967) to determine the potential evapotranspiration ratio for different forest tree species and the multiplier for temperature ($Y_t = 4 \cdot (D_{\max} - x) \cdot (x - D_{\min}) / (D_{\max} - D_{\min})^2$) as a function of the forest growth (Kellomäki & Kolström 1992).

The species-specific parameters used for modelling forest dynamics under potential climate changes are given in Table 17.

Table 17. Species Parameters for Forest Gap Model Calculations

Species	Age _{max} yr	HGT _{max} m	DBH _{max} m	L	minPet ratio	SED _{max}	D _{min}	D _{max}
	1	2	3	4	5	6	7	8
<i>Picea abies</i>	290	45	1.3	1	0.94	55	140	2640
<i>Pinus sylvestris</i>	350	43	1.6	3	1.2	38	430	1985
<i>Betula pendula</i>	150	31	0.9	3	1.04	130	40	1985
<i>B. pubescens</i>	120	22	0.5	2	0.94	74	40	2100
<i>Populus tremula</i>	180	33	1.4	3	1.0	68	20	3380
<i>Alnus incana</i>	70	24	0.6	1	1.02	78	120	1985
<i>A. glutinosa</i>	130	32	1.1	2	0.94	28	1000	3380
<i>Quercus robur</i>	600	40	2.0	2	1.04	28	1040	3275
<i>Fraxinus excelsior</i>	230	37	1.3	3	1.04	36	1300	3600
<i>Ulmus laevis</i>	180	32	1.0	2	1.0	36	600	3600

1. AGE_{max} = maximum age (Laas, 1967; Tappo, 1982)
2. HGT_{max} = maximum height (Tappo, 1982)
3. DBH_{max} = maximum diameter (Tappo, 1982)
4. L = light response category (1 - shade tolerant, 2 - intermediate, 3 - shade intolerant) (expert estimation)
5. minPet ratio = potential evapotranspiration allowing tree growth, as species specific index of drought tolerance. It is the quotient of PET and average annual precipitation (Holdridge, 1967)
6. SED_{max} = maximum yearly seedlings establishment scaled to plot (Laas, 1967; Holdridge, 1967)
7. D_{min} = minimum degree-day limit (Paal et al., 1989)
8. D_{max} = maximum degree-day limit (Paal et al., 1989)

Calculations were made for current climatic conditions and for possible climatic change, incorporating a +4 °C increase in temperature and a 10% increase in annual precipitation, in five locations in Estonia (Table 18).

Table 18. Climatic Variability of the Study Sites Incorporated in the Simulation Process

Study Sites	Current climatic conditions*			Simulated climate change**		
	GDD	PET ratio	AP	GDD	PET ratio	AP
1. Virtsu	2503.7	0.82	620	3609.9	0.92	682
2. Tudu	2257	0.72	670	3264	0.8	737
3. Kärevere	2373	0.85	584	3395.5	0.95	641
4. Võhma	2366.7	0.72	694	3392.3	0.8	763
5. Risti	2372.5	0.72	690	3447.7	0.8	762

GDD - annual sum of growing-degree days temperature (above 0°C)

PET ratio - potential evapotranspiration ratio, mm/mm

AP - annual precipitation

* Data of J. Jaagus from the Institute of Geography, Tartu University

** Climate change: increase in temperature of +4 °C and +10% annual precipitation.

We carried out two types of sensitivity experiments. In the first set we used incremental scenarios where the forest grew from bare ground in climatic conditions altered from the current conditions (+4 °C, +10% AP) from the very beginning (scenario 2).

Climate Change Scenarios

Climate change scenarios were constructed assuming that transient climate change occurred linearly over 100 years. In our experiments, we grew forest from bare ground in the current climatic conditions. From year 100 (scenario 3) or 200 (scenario 4) we

linearly changed the mean monthly temperature and precipitation to simulated equilibrium $2 \times \text{CO}_2$ (twofold increase in CO_2) levels and then held the climate constant until the year 500.

Scenario 1

Current climatic conditions continued over 500 years. Forest grew from bare ground.

Scenario 2

Climate change scenario with a doubling of the level of CO_2 ($+4^\circ\text{C}$, 10% AP) was applied before forest development (year 0) and was held constant over 500 years.

Scenario 3

Transient climate change started from the year 100 and then linearly changed during the next 100 years and held constant during the years 200-500. Before year 100 forest grew from bare ground under current climatic conditions.

Scenario 4

Transient climate change takes place from the year 200 until the year 300. After that (i.e. from the year 300 until the year 500) climate held constant.

Selection of Study Sites

We used the Forest Gap Model to simulate the effects of climate change for five relatively species rich forest stands (Table 19) in different regions of Estonia (Figure 12).

Figure 12. Forest Cover (%) by Counties of Estonia. Location of Study Sites

Table 19. Forest Growth Simulation Sites

No, Study Site	County	Latitude	Longitude	Present Species*
1. Virtsu	Läänemaa (W)	58.6 N	23.5 E	<i>Pinus sylvestris</i> , <i>Alnus incana</i> , <i>Picea abies</i> , <i>Quercus robur</i> , <i>Ulmus laevis</i>
2. Tudu	Lääne-Viru (N)	59.2 N	27.0 E	<i>Betula pendula</i> , <i>Picea abies</i> , <i>Pinus sylvestris</i> , <i>Alnus</i> <i>glutinosa</i> , <i>Populus tremula</i> , <i>Fraxinus excelsior</i>
3. Kärevere	Tartumaa (E)	58.4 N	26.5 E	<i>Betula pendula</i> , <i>Picea abies</i> , <i>Alnus glutinosa</i> , <i>Fraxinus</i> <i>excelsior</i> , <i>Alnus incana</i> , <i>Pinus</i> <i>sylvestris</i>
4. Võhma	Viljandimaa (C)	58.6 N	25.5 E	<i>Betula pubescens</i> , <i>B. pendula</i> , <i>Populus tremula</i> , <i>Alnus</i> <i>glutinosa</i> , <i>A. incana</i>
5. Risti	Harjumaa (NW)	59.0 N	24.0 E	<i>Pinus sylvestris</i> , <i>Betula</i> <i>pubescens</i> , <i>Picea abies</i> , <i>Alnus</i> <i>incana</i>

* Data by H. Rebassoo from the Estonian Forest Service

Results of the V&A Assessment

The model results for forest sample plots in Estonia are given in Figures 13-20, which illustrate both the autogenic and allogenic succession of different forest stands in Estonia.

The simulation was built up step by step. Forest growth was modelled from bare ground with the present species associations, until the year 500, with climate modifications according to the different scenarios.

Scenario 1 (control)

The results of modelling showed intense forest growth during the first 50-70 years, which is in accordance with the empirical data collected by the Estonian Forest Service about mature and overmature forests (Statistical Yearbook 1994; Yearbook of Forest 1995). In all sample plots for which calculation were made the total biomass of forest over 100 years of age was about 135-145 t/ha until the 500th year. A slight decline in stand basal area occurred after 100 years in the Virtsu and Kärevere area (Figures 13 and 14). The species composition remained unchanged until the 100th year. This shows that the selection of parameters for the modelling framework was successful.

Comparison of real values of average biomass, for mature forest stands in the different counties where our sample plots were located (Yearbook of Forest 1995), with simulated average biomass values for forest stands showed good accordance (Table 20).

Figure 13. Computation Example of Forest Biomass (t/ha) and Basal Area (m²/ha) Dynamics of Forest Stands in Different Counties of Estonia During 500 Years in Current Climate Conditions

Figure 14. Species Composition and Biomass Dynamics in Climate Conditions (Control) Calculated Using the Forest Gap Model for Five Sample Plots. Climate is Held Constant over 500 Years

Scenario 2

According to the possibilities of the FGM and the recommendations of the U.S. Country Studies Program, in scenario 2 the transient climate change was applied before the start of forest growth (year 0) and then the climate was held constant over the period 0-500 years. Forest growth from bare ground in climatic conditions altered from the very beginning was modelled and the results are presented in Figures 15 and 16.

Figure 15. Total Biomass (t/ha) and Basal Area (m²/ha) of Forest Stands Which Grew on Bare Ground and Under Changed Climate Conditions in Sample Plots

Figure 16. Simulated Changes in Species Composition in Forest Sample Plots. Climate Change (2xCO₂, +4°C, +10% a.p.) Began Before Forest Development

A comparison of the forests' total biomasses and basal areas with the control showed a drastic decrease in both parameters in the Kärevere, Risti and Virtsu areas, but not in Tudu and Võhma in central Estonia.

The calculations predicted rapid changes in the species compositions of forest stands in all selected sites. In general, the trend was towards the impoverishment of the species composition of forest stands. The biomass of *Populus tremula* more than doubled in the Tudu, Võhma and Kärevere areas. A rapid increase may also occur in the biomass of *Betula pubescens* in Virtsu and *Alnus glutinosa* in the Tudu and Võhma areas. *Quercus robur* may become a dominant species in Virtsu

Scenario 3

In the case of transient climate change from year 100 to year 200, our calculation showed a linear biomass decrease until the year 400 in the Kärevere, Risti and Virtsu

areas. In the Tudu and Võhma areas the slight decline in forest biomass and basal area was soon replaced by a new increase due to the intense growth of *Populus tremula*. In the coastal area (Virtsu) *Quercus robur* and *Betula pubescens* became dominant species in the forest stand (Figures 17 and 18).

Figure 17. Simulated Changes in Total Biomass (t/ha) and Basal Area (m²/ha) in Forest Sample Plots. Horizontal Axis Represents Runs for 100 Years at Each Site in Current Climate Conditions. Then Altered Linearly over Next 100 Years to Reach Simulated (2xCO₂, +4°C, +10% a.p.) Climate and Run Until the Year 500 in New Climate Conditions

Figure 18. Simulated Changes in Species Composition and Biomass in Sample Plots. Horizontal Axis Represents Runs for 100 Years at Each Site in Current Climate Conditions. Then Altered Linearly over Next 100 Years to Reach Simulated (2xCO₂, +4°C, +10% a.p.) Climate and Run Until the Year 500 in New Climate Conditions

Scenario 4

Transient climate change started at year 200 and continued until the year 300. Biomass and basal area reached their lowest levels in all sites after 70-80 years. The changes in forest stand composition were similar to those in scenario 3 (Figures 19 and 20).

Figure 19. Simulated Changes in Total Biomass (t/ha) and Basal Area (m²/ha) in Sample Plots. Horizontal Axis Represents Runs for 200 Years at Each Site in Current Climate Conditions. Then Altered Linearly over Next 100 Years to Reach Simulated (2xCO₂, +4°C, +10% a.p.) Climate and Run Until the Year 500 in New Climate Conditions

Figure 20. Simulated Changes in Species Composition and Biomass in Sample Plots. Horizontal Axis Represents Runs for 200 Years at Each Site in Current Climate Conditions. Then Altered Linearly over 100 Years to Reach Simulated (2xCO₂, +4°C, +10% a.p.) Climate and Run Until the Year 500 in New Climate Conditions

Responses to climatic change at each site were strongly dependent on the age of trees. There were, however, high variations between the sites in different regions of Estonia.

Economic Analyses

The decrease in the total biomass per hectare according to the simulated climate change scenarios brought about a rapid decrease in forest value per ha when only the tree species occurring in current forest ecosystems were taken into account. A summary of the five sample plots used in the modelling framework and their comparison with the control (scenario 1), shows that climate change may decrease the total biomass and the forest value per ha by about 35% in the case of scenario 2, by 27% in the case of scenario 3, and by 21% in the case of scenario 4 (Fig. 21, Table 20).

Figure 21. Differences Between Averages of Simulated Total Biomass (t/ha) of Forest Stands Growing in Current Climate Conditions (Series 1) and in Different Climate Change Scenarios (Series 2-4) from the Beginning of Trees Germination Until 500 Years of Forest Existence. Results of the Forest Gap Model Calculations. Numbers of Series Correspond to the Numbers of Scenarios

Such a prediction of economic hazards in the forestry sector is a bit speculative, since the potential impact of climate change on forests and terrestrial vegetation will probably also result in the invasion of new species. This will alter the ecosystem composition and, evidently, the total biomass of forests, and its economic value may change.

If we could include into the modelling system the parameters of forest tree species from Central Europe, then the results of forests species composition, biomass and economic assessments may be entirely different.

Table 20. Economic Evaluation** of the Impact of Simulated Climate Change on Forest Biomass*** (Average of 500 years). Continued on the Next Pages**

Region (County)	Mean Forest Biomass on Forest Land 1994* t/ha	Forest Value at		Scenario 1		
		Auctions		Current Climate Conditions		
		in 1994**		Biomass	Value/ha	
		EEK/m ³	EEK/t	t/ha	EEK	USD
Tudu (Lääne- Viru)	114	248	298	129	38442	3204
Võhma (Viljandi)	182	157	187	131	24497	2041
Virtsu (Lääne)	114	176	206	125	25750	2146
Kärevere (Tartu)	170	205	242	130	31460	2622
Risti (Harju)	126	223	268	128	34304	2859

Region (County)	Scenario 2					
	Climate is Changed Before the Beginning of Forest Development					
	Biomass		Value/ha			
	t/ha	Differences from Sc 1	EEK	USD	Differences from Sc 1	
					EEK	USD
Tudu (Lääne-Viru)	120	-9	35760	2980	-2682	-224
Võhma (Viljandi)	123	-8	23001	1917	-1496	-124
Virtsu (Lääne)	60	-65	12360	1030	-13390	-1116
Kärevere (Tartu)	41	-89	9922	827	-21538	-1795
Risti (Harju)	73	-55	19564	1630	-14740	-1229

Table 4 continued

Region (County)	Scenario 3					
	Climate is Changed at Year100 of Forest Existence					
	Biomass		Value/ha			
	t/ha	Differences from Sc 1	EEK	USD	Differences from Sc 1	
					EEK	USD
Tudu (Lääne-Viru)	126	-3	37548	3129	-894	-75
Võhma (Viljandi)	121	-10	22627	1886	-1870	-155
Virtsu (Lääne)	74	-51	15244	1270	-10506	-876
Kärevere (Tartu)	64	-66	15488	1291	-15972	-1331
Risti (Harju)	87	-41	23316	1943	-10988	-916

Region (County)	Scenario 4					
	Climate is Changed at Year 200 of Forest Existence					
	Biomass		Value/ha			
	t/ha	Differences from Sc 1	EEK	USD	Differences from Sc 1	
					EEK	USD
Tudu (Lääne-Viru)	120	-9	35760	2980	-2682	-224
Võhma (Viljandi)	122	-9	22814	1901	-1683	-140
Virtsu (Lääne)	89	-36	18334	1528	-7416	-618
Kärevere (Tartu)	79	-51	19118	1593	-12342	-1029
Risti (Harju)	96	-32	25728	2144	-8576	-715

* In the calculation of forest biomass for 1994 the growing stock volume by tree species on forest stands (Yearbook of Forest 94, 1995) was used and 25% added for branches and leaves

** Prices of forest at auction for different counties are presented for 1994 (Yearbook of Forest 94, 1995)

*** Average biomass (t/ha, n=500) of the forest stands was calculated for the different sample plots used in Forest Gap Model calculations

**** In the economic evaluation of the changes in forest biomass (t/ha) as a result of climate changes it was assumed that forest biomass is given as a fresh biomass.

1 USD = 12 EEK in 1994

Discussion and Conclusions

The Forest Gap Model generalizes the possible successional directions of forest ecosystems in changing climatic conditions. This prediction is based solely on a knowledge of the ecology of the tree species of contemporary Estonian forests. The results of FGM calculations indicate that the competitive ability of several deciduous tree species (*Populus tremula*, *Betula* spp., *Quercus robur* and others) could increase significantly in conditions of rising temperature with a subsequent increase of their biomass in the ecosystem, particularly in Central Estonia. The biomass of conifers, currently the dominants in at least 70% of Estonian forests, might decrease in the case of a potential doubling of CO₂ in the atmosphere and a warming of the climate.

The results of the simulation show that the responses of forests to transient climate change depend on the age of trees and the stage of their development, but also on local conditions. A drastic inhibition of biomass and basal area formation in the present forest tree species occurred from the very beginning of their development in the case where climatic conditions were altered from the very beginning. A logical

consequence of such a situation would be the replacement of the present species in forest ecosystems by those of more southern distribution.

The analysis of the diagram given by Holdridge (1967) Life Zone Classification Model showed that the forest vegetation of Estonia belongs to the class 'Moist forest' and the postulated climate change would not change the main ecosystem type. Possible changes in the species composition of forest ecosystems were predicted by the comparison of Estonian forest vegetation with that of areas characterized by a warmer climate. It was shown that the invasion of many new tree species, in particular of *Fagus sylvatica*, *Carpinus betulus* and *Quercus petraea*, is expected. It should be noted that the distribution area of these species is, even nowadays, not very far from Estonia. For example, according to Hulten (1950), the northern limit of the distribution area of *Carpinus betulus* is in southern Latvia, i.e. in an area with only a slightly warmer climate than Estonia. Consequently, it is probable that if the real changes do take place, a decrease in forest stand biomass and basal area will only occur during the relatively short transitional phase which is needed for the migration of the above mentioned tree species. If human activity accelerates the invasion of new tree species, e.g. by planting and/or sowing them in forest clearcuts, the transitional phase will be even shorter.

In Estonia, the heterogeneity of the landscape, particularly the distribution of various soils, will become an important factor determining forest responses to climate change.

In more fertile soil conditions, one could expect the development of *Fagion* forest communities, while in more oligotrophic conditions, the development of *Quercion* communities is expected. However, many landscape characteristics are not

incorporated in the framework of the Forest Gap Model which means that precise predictions are difficult to make.

Also, many forest ecosystems are currently under considerable pressure from human activities. Firstly, excluding the protected areas, all forest stands in Estonia are clearcut after certain time intervals. The regeneration of the forest communities depends not only on the technology of clearcutting, but also on the subsequent management of the clearcut areas (fertilization, use of herbicides to suppress herbaceous species, sowing and planting of trees, cutting deciduous trees to favour conifers, burning). The herbivory of large mammals may also influence the direction of changes. Secondly, environmental stresses of anthropogenic origin can not be ignored. Environmental pollution is a serious problem, especially in the north-east of Estonia (Liblik & Kundel 1995), but the impact of air pollution on forest ecosystems cannot be ignored elsewhere. Since conifers are typically more vulnerable to air pollution, successional changes due to climatic changes may significantly be accelerated by air-pollution induced processes.

use the Thornthwaite and modified Penman methods (all the methods described in the U.S. Country Studies Guidance for the V&A Assessment) for calculation of potential evapotranspiration. All the three methods were used in the current assessment.

The soil moisture balance is expressed using effective precipitation (positive component), and surface runoff, sub-surface runoff, potential evapotranspiration, and baseflow (negative components) values.

The WatBal model needs a lot of meteorological and hydrological data. The data have been obtained from the Estonian Institute of Meteorology and Hydrology. The monthly mean values of precipitation, air temperature, and rivers runoff were used. The data on precipitation of the studied river basins were obtained from the four meteorological observation stations, which were located near the study areas. The amounts of precipitation are expressed as averaged values which are interpolated into the grid cells. A special program was created for calculation of spatial mean values for the studied river basins. The monthly mean values of temperature as well as long-term mean values of sunshine duration, relative humidity, and wind speed were collected from the central meteorological observation stations of the studied catchment areas. The runoff data of the lowest discharge stations of the observed rivers were used for calibration and validation of the water balance model. The baseline period for the water resources vulnerability assessment was the same (1961-1990) as for the climate scenarios.

Three GCM scenarios (GISS, CCCM, GFDL30), one transient scenario (GFDL), and a number of incremental climate change scenarios were used in the modelling process. Increases in temperature of 2°, 4°, and 6°C were combined with no change, and with $\pm 10\%$ and $\pm 20\%$ changes in precipitation.

Selection of Study Sites

The territory of Estonia is divided into 27 main river basins which areas vary from 105 to 7840 km². Most of the river basins are below 1000 km² in area. Although small in area, the river basins have remarkable spatial and temporal variabilities in their hydrologic parameters.

Three river basins of different hydrologic regimes in different landscape regions of Estonia were selected for study areas (Figure 22). The criteria for their selection were the following: (1) well defined area; (2) good quality of the data on both precipitation and runoff; and (3) absence or minimum impact of human activity on the runoff regime.

The Pärnu River catchment area is the biggest among the study areas (Table 21). Climatic and hydrologic conditions as well as landscapes here are typical of the central and western Estonia. The upper course of the river flows through slightly rolling till plains covered with fields and meadows and with sparse rural settlements. The lower course of the river goes through a very flat varved clay plain covered with forest and peatland. The Kunda River, which flows through the North-Estonian Limestone Plateau, is a typical stream of the northern part of Estonia. Its stream channel is full of springs. The catchment area of the Väike-Emajõgi River is located in the southern Estonia, which is characterized by hillocky

Results of the V&A Assessment

Results of the Hydrologic Vulnerability Assessment

The WatBal model was a very suitable tool for modelling possible effects of climate change on the rivers runoff in Estonia. The first decade of the baseline period (1961-1990) was used for the calibration of the model, i.e. for determining the model parameters. The two following decades were used for the validation of the model. The last decade of the baseline period (1981-1990) is characterized by higher precipitation and runoff compared to the average values. These characteristics cause errors in modelling, particularly in winter. The biggest error is observed in the Kunda River basin, which can be explained by the karst phenomena.

The maximum discharges are observed in April, during the period of snow melting. The Pärnu River catchment area is characterized by higher precipitation and lower infiltration values while the runoff fluctuations are the highest. Due to the karst phenomena, the runoff in the Kunda River basin in summer is much higher because of a significant sub-surface inflow. A decrease in the maximum runoff is observed in November because of an increase in precipitation.

The time series of annual mean runoffs of the study areas are presented in Figure 24. A remarkable increase in the rivers discharge during the second half of the baseline period (maximum precipitation in the 1980s) is evident. At the same time, much lower runoff in

Table 23. Hydrologic Vulnerability Assessment for the Kunda River Basin

	Change in Precipitation (%)	Change in Temperature (°C)	Change in Runoff (%)	Annual Storage Capacity and Annual Runoff Ratio
GISS	36	4.0	53	0.468
GFDL30	20	5.1	36	0.571
CCCM	21	4.2	24	0.575
GFDL transient, 4th decade	2	1.3	2	0.701
GFDL transient, 7th decade	3	3.2	6	0.673
GFDL transient, 10th decade	20	4.3	30	0.550
Incremental	0	4.0	-1	0.722
Incremental	10	4.0	12	0.636
Incremental	20	4.0	26	0.566
Incremental	-10	4.0	-14	0.827
Incremental	-20	4.0	-25	0.956

Table 24. Hydrologic Vulnerability Assessment for the Väike-Emajõgi River Basin

	Change in Precipitation (%)	Change in Temperature (°C)	Change in Runoff (%)	Annual Storage Capacity and Annual Runoff Ratio
GISS	35	3.9	68	0.669
GFDL30	24	4.9	45	0.778
CCCM	16	4.1	24	0.908
GFDL transient, 4th decade	5	1.2	8	1.038
GFDL transient, 7th decade	4	3.1	8	1.046
GFDL transient, 10th decade	20	4.3	41	0.800
Incremental	0	4.0	-4	1.171
Incremental	10	4.0	14	0.987
Incremental	20	4.0	33	0.847
Incremental	-10	4.0	-20	1.413
Incremental	-20	4.0	-35	1.777

The model results indicate a substantial variability in the rivers discharge. The GISS model gives the highest increase in precipitation and runoff (weighted mean value for the whole study area - 66%), while the CCCM gives the lowest mean value (30%). Higher sensitivities of discharge to climate change are observed in the Väike-Emajõgi River and in the whole hydrologically studied area of Estonia. Lower values are characteristic to the Pärnu and Kunda River. It is necessary to emphasize that according to the transient scenario, the most essential increase in annual runoff would occur during the last quarter of the transient period.

Table 25. Hydrologic Vulnerability Assessment for the Whole Territory of Estonia

	Change in Precipitation (%)	Change in Temperature (°C)	Change in Runoff (%)	Annual Storage Capacity and Annual Runoff Ratio
GISS	35	3.8	66	0.569
GFDL30	21	5.0	38	0.684
CCCM	17	4.1	30	0.728
GFDL transient, 4th decade	3	1.2	6	0.892
GFDL transient, 7th decade	4	3.1	11	0.848
GFDL transient, 10th decade	20	4.3	40	0.674
Incremental	0	4.0	0	0.942
Incremental	10	4.0	18	0.804
Incremental	20	4.0	36	0.697
Incremental	-10	4.0	-16	1.123
Incremental	-20	4.0	-30	1.358

The modelling results of mean monthly discharge in the case of $2\times\text{CO}_2$ concentration are presented in Figures 25-28. The GF01 is the abbreviated variant of the GFDL transient scenario for the 10th decade. According to the GCM scenarios, the runoff would strongly increase in autumn and winter. The GISS model shows an increase in runoff since July already. The maximum runoff in November would become the highest during the whole year instead of the observed monthly maximum in April. This is caused by the expected increase of precipitation in autumn.

Figure 25. Runoff in the Pärnu River Basin in the $2\times\text{CO}_2$ Scenario

Figure 26. Runoff in the Kunda River Basin in the $2\times\text{CO}_2$ Scenario

Figure 27. Runoff in the Väike-Emajõgi River Basin in the $2\times\text{CO}_2$ Scenario

Figure 28. Runoff in the Total Study Area in the $2\times\text{CO}_2$ Scenario

The spring floods occur a month earlier, in March instead of April. Their intensity decreases essentially in the Pärnu and Kunda River basins. The other rivers maintain their spring floods, which also occur in March. These substantial changes can easily be explained via the changes in snow cover and the rivers ice regime. Warming in winter makes the weather unstable. Frequent melting periods prevent the formation of a thick ice cover, and due to the meltwater, the rivers have relatively high runoffs.

These estimates are made using the Priestly-Taylor method for calculation of potential evapotranspiration. The values obtained by this method are 15-18 % lower than the values obtained using the Thorntwaite and the modified Penman methods. The model results using the Thorntwaite method show lesser changes in the rivers discharge. The runoff model results using the Priestly-Taylor method are not sensitive to an increase in temperature and potential evapotranspiration. Changes in runoff depend mainly on the changes in precipitation. The Thorntwaite method, on the contrary, shows very accurately the changes in temperature. The increase in mean temperature of 1°C will cause the decrease in mean annual discharge by 2-4 %. The modified Penman method gives intermediate results.

A special research has proved that climate warming results in great changes of the snow cover pattern in Estonia. The extent and duration of the sea ice cover decrease many times. The ice-free Baltic Sea warms up the coastal areas in the western and northern Estonia. A permanent snow cover remains mainly on uplands. As major part of the Väike-Emajõgi catchment area is located on the Otepää Heights (up to 200 m above sea level), the spring maximum in runoff is caused by abundant meltwater.

Results of Water Resources Supply and Demand Models by Climate Change

Scenario

There are about 1.000 registered water consumers (different institutions of water extraction) in Estonia. General water use data of recent years (1990 - 1994) are presented in Table 6. The economic crisis during the post-soviet period has caused a decrease in water consumption, in the volume of waste water, and in the pollution load.

A long-period mean river runoff in Estonia is 11.7 km³ per year or 260.000 m³ per km². The surface water consumption in 1994 was 1.73 billion m³. The surface water in Estonia is mainly used as cooling water in thermal power plants (80 % of total consumption). The remaining 20% is used in industrial enterprises and for municipal water supply in Tallinn and Narva. Since 1992 the major users of surface water, the thermal power plants, have reduced water consumption because of lesser need for energy.

Table 26. Surface Water Consumption in Estonia (km³ / year)

Water Consumption	1990	1991	1992	1993	1994
Total Water Demand	2.98	2.77	2.44	1.81	1.73
Industrial Water Use	0.16	0.16	0.12	0.08	0.07
Energy-Related Water Use	2.44	2.23	1.98	1.44	1.37
Agricultural Water Use	0.05	0.04	0.03	0.01	0.01
Domestic Water Use	0.12	0.10	0.10	0.10	0.09

Major fresh water aquifers in Estonia lie in limestones and sandstones of the bedrocks.

Those ground water sources of high quality are widely used in water supply, especially in

towns and villages. The available supply of ground water is sufficient to cover the need of all consumers, except in Tallinn and the industrial district of the northeastern Estonia.

During the last 50 years, a general demand for water has constantly increased due to the growth in population and urbanization. The growth in population has stopped by now. In 1994 the demand for domestic water per capita was 165 l a day. The trend of municipal water demand is slightly increasing.

The modelled values of annual mean runoff using the climate change scenarios and the water demand by different consumers calculated for the year 2075, are presented in Table 27. A long-term perspective water demand is estimated using the following coefficients: (1) domestic water use - 3.25; (2) agriculture - 3.60; (3) energy-related water use - 1.50; (4) industry - 2.25; and (5) weighted mean coefficient for total water demand - 1.54. We can see that the estimated total water demand does not exceed the rivers runoff values in any climate change scenarios. Possible climate change in the future will not cause any serious consequences to the water resources of Estonia.

Table 27. Water Resources Supply and Demand in Year 2075 in ($10^9 \text{ m}^3/\text{yr}$) Estimated Using the WatBal Model

Scenario	Total Water Supply	Total Water Demand	Industrial Water Use	Energy-related Water Use	Agricultural Water Use	Domestic Water Use
BASELINE	11.89	2.98	0.16	2.44	0.05	0.12
GISS	21.14	4.59	0.36	3.66	0.18	0.39
CCCM	16.31	4.59	0.36	3.66	0.18	0.39
GFDL30	17.07	4.59	0.36	3.66	0.18	0.39
GFDL-4	12.60	4.59	0.36	3.66	0.18	0.39
GFDL-7	13.20	4.59	0.36	3.66	0.18	0.39
GFDL-10	16.65	4.59	0.36	3.66	0.18	0.39
T+4,P0	11.89	4.59	0.36	3.66	0.18	0.39
T+4,P+10	14.03	4.59	0.36	3.66	0.18	0.39
T+4,P+20	16.17	4.59	0.36	3.66	0.18	0.39
T+4,P-10	9.99	4.59	0.36	3.66	0.18	0.39
T+4,P-20	8.32	4.59	0.36	3.66	0.18	0.39

Discussion and Conclusions

The results of modelling indicate that an increase in temperature of 4°C and precipitation of 20% will be followed by an increase in annual runoff of rivers by 20-40 %. Significant changes will occur in annual course of discharge. The runoff maximum in spring will decrease, and move on earlier period. The runoff during autumn and winter months will strongly increase..

The most essential decrease of the maximum runoff in spring takes place in the western part of Estonia. It is a region of maritime climate where the duration of snow cover shortens very much.. At the same time, in the eastern Estonia, a stable snow cover and a maximum runoff in spring remain. Small rivers in the regions of till plains and moraine hillocks are the most vulnerable to climate change. Runoff is the least vulnerable in the regions of limestone plateaus and karst fields.

There are regional differences in the distribution of water resources. For example, in the northern part of Estonia (the drainage area of the Gulf of Finland), about 20% of the total volume of fresh water is available on the territory of 9.300 km². The biggest cities, including the capital city Tallinn and many industrial centres, which have serious problems with storage and distribution of water to the consumers, are concentrated in this region. In some places the water of rivers and brooks is unfit for use because of insufficient purification of waste water. In the periods of minimum runoff these strams may often be overloaded with pollutants. Therefore, complete (both biological and chemical) purification of waste water is of primary importance.

The modelling approaches presented in this study have their own drawbacks, for example they could be analysed more thoroughly from the viewpoint of socio-economic development. The discharge data should correspond to the water quality data to enable better integrated management of small river basins.

The results of the water resources vulnerability assessment show a strong dependence of regional changes in runoff on local topography and landscape features. Unfortunately, these aspects can't be reproduced on spatial scale by the models.

Modelling the Influence of Climate Change on Groundwater Regime in Estonia

Groundwater is the main drinking-water resource in Estonia, satisfying the water demand for socio-economic development everywhere in the country. The main artificial factors influencing the natural regime of groundwater are water consumption and dewatering of mines and quarries. Approximately $0.35 \times 10^6 \text{ m}^3$ of groundwater is used per day, meeting 60-70 % of the municipal, industrial and agricultural demands of water consumption. Only in Tallinn and Narva the consumption of surface water exceeds that of groundwater..

The study contains analysis of the groundwater level temporal variations, and presents some regional differences in the change of the level. The influence of possible climate change on the groundwater regime and seasonal variability are estimated using the WatBal Model.

Data Sources

Regular observations of the groundwater regime in Estonia were started in 1946. The planned development of geohydrological observation network was initiated by the Estonian Geological Survey in 1960. Groundwater regime observations were carried out in all aquifers of Estonia.

According to the Estonian Groundwater Monitoring Program, the water regime data are collected from 504 wells in 7 study areas, which represent nearly all geohydrological types of the Estonian bedrock (Groundwater ..., 1995). The groundwater levels are normally measured with some interval series to the "standard" of maximum 10 measurements per month, depending on ambition and economy. It is obvious that information about short time changes are lost when the interval is increased.

The data, collected from the Estonian Geological Survey on 6 observation sites of different landscape regions, are used in this study (Table 28). Special analysis were carried out to assess possible influences of the climate change on the groundwater regime in different geohydrological regions. (Figure 29).

Figure 29. Location of Studied Groundwater Observation Wells

Table 28. Characteristics of the Observation Wells

Number and Location of the Observation Well	Geological Index of Waterbearing Stratum	Lithological Type of Waterbearing Rocks	Observation Period	Altitude of the Well-Top
214 Lääne-Viru county, Sämi	O ₂ ls	limestone	1961-1995	69.68
999-C Lääne-Viru county, Väike-Maarja	S ₁ jr	limestone	1972-1995	121.15
1054 Jõgeva county, Tooma	S ₁ rk	limestone, dolomite	1969-1995	77.24
1155 Viljandi county, Lalsi	D ₂ nr	dolomite	1973-1995	36.34
1165 Viljandi county, Õisu	D ₃₋₂	sandstone	1973-1995	60.71
1207 Põlva county, Piigaste	D ₃₋₂	sandstone	1968-1994	102.73

The observation wells in Sämi and Väike-Maarja are typical of limestone plateaus and karst fields. In this region, the conditions for groundwater recharge are the most favourable (Pandivere..., 1993). The infiltrated precipitation issue in the form of springs, and some of them open in the river beds. The Õisu and Piigaste wells are located in the southern part of Estonia, and are typical of the regions with hilly relief. The aquifers here are lying in sandstones.

Methods

A successful application of groundwater models requires accurate and representative data. The time series of groundwater levels reflect the changes in storage of the aquifer, and thus also the recharge or discharge of the aquifer. One simple way to examine the possible climate change influence on the groundwater regime is to establish some relationships between the main water balance elements (precipitation and runoff) and the groundwater level (Figure 30).

Figure 30. Relationships Between Precipitation and Groundwater Level (Above) and Between Runoff and Groundwater in the Sāmi Study Area

The seasonal patterns of precipitation and runoff in the analysed regions are similar, but the correlation between runoff and groundwater level is higher than between precipitation and groundwater level. The groundwater level series are similar to river discharge series, and it can be treated statistically in the same way (Svensson & Olin, 1994). We have found out that the correlation between the water table in boreholes and the rivers discharge is possible. Hydraulic continuity exists between the rivers and the aquifers, while the groundwater gradients are directed to the river during dry seasons.

Natural Fluctuations

The underground hydrosphere in Estonia represents a system of interconnected aquifers which is influenced by climatic factors and human activity. In the areas where groundwater is recharged mainly from rainfall, the changes in groundwater level depend on the characteristics and state of the aquifer and overlying soil. The relationship becomes stronger when the water table reaches the ground surface. This makes the groundwater table to follow the annual rhythm of seasonal changes. Corresponding fluctuations occur in the groundwater table, where changes in level may be either relatively rapid, as in the case of seasonal variation, or slow lasting for many years. Evaporation, which is the most important outflow component of the water balance, has a significant impact on groundwater level changes. In some areas the groundwater recharge may be derived directly from rainfall (The Pandivere Upland in northern Estonia) and in other areas from infiltration of the surface water.

The average monthly records from the period 1961-1990 are shown in Figure 31. These graphs illustrate the regional differences and some individual features of the selected wells, although the seasonal patterns of the groundwater regime in four analysed regions are similar to each other. The average and extreme values in the studied wells are presented in Table 29.

Figure 31. Long-Period Groundwater Level Fluctuations (36-Month Moving Average)

In Figure 31 one can see a pronounced rise in water level during the period of 1978-1991, which was dominated by the increase in precipitation. The rise of water level in winter in the 1990s is partly an effect of the recent mild winters with little accumulation of snow. During the studied period, the annual mean water level varied on the Pandivere Upland from 1.34 m (in Sämi) to 2.29 m (in Väike-Maarja), and in the southern Estonia, from 0.53 m (on the Sakala Upland) to 0.61 m (on the Otepää Upland).

Table 29. Natural Groundwater Levels in Studied Wells (m from Surface).

Observation Well	Observation Period	Mean	Minimum	Maximum	Min. year	Max. year
VK214	1961-95	3.08	4.37	1.34	3.84	2.50
VK999-C	1972-80, 83-95	16.59	19.96	12.39	17.69	15.40
VK1054	1969-95	0.81	1.37	0.41	0.93	0.63
VK1155	1973-95	0.74	2.55	0.07	1.25	0.43
VK1165	1973-95	1.78	2.64	0.90	2.05	1.52
VK1207	1968-94	3.51	4.60	2.89	3.85	3.24

The runoff information can be used to illustrate the recent climatic variations related to the other water balance elements, but also to the groundwater regime. The figures of the water

balance and the groundwater level on the Sămi observation area are given in Table 30. The correlation between the rivers runoff changes and the groundwater level time series is relatively high..

Table 30. Hydrologic and Climatic Characteristics of the Sămi Study Area

Period	t°	Precipitation (mm/y)	Runoff (mm/y)	Evaporation (mm/y)	Groundwater Level (m from Surface)
1961-1965	4.8	592	309	354	3.19
1966-1970	4.1	635	323	312	3.13
1971-1975	5.7	641	256	385	3.36
Dry Period 1961-1975	4.9	623	296	350	3.23
1976-1980	4.1	654	307	347	3.13
1981-1985	5.0	667	362	305	2.92
1986-1990	5.4	700	379	321	2.76
Wet Period 1976-1990	4.8	674	349	324	2.94
Mean	4.9	648	323	315	3.08

An example of comparing the hydrologic characteristics in time series is provided by dividing the runoff series into "dry" and "wet" years, based on annual mean precipitation. It can be assumed that notable changes in the groundwater regime occur when an average 100 mm change in the mean precipitation is recorded. A comparison of the difference in groundwater level between dry and wet periods shows a well-defined tendency (Table 30).

Modelling the Impact of Climate Change on Groundwater Level

The results of prognosticated groundwater levels using different climate change scenarios are presented in Tables 31-34 and the mean annual values in Table 35. Changes in mean annual water level and their seasonal variabilities have been calculated for three incremental

scenarios (T +4°C and P 0%; T +4°C and P +20%; and T +4°C and P -20%) and for one GCM equilibrium scenario (GISS).

The modelling results indicate not a very high changeability of the groundwater levels. Higher sensitivity is observed in the Silurian-Ordovician area where the bedrock consists of limestones and dolomites. The Devonian area in southern Estonia consisting of sandstones is less sensitive to the climate change.

Table 31. Groundwater Regime Vulnerability to Climate Change in the Sāmi Study Area (VK214).

Model	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline	3.01	3.18	3.26	2.48	2.44	2.96	3.32	3.44	3.46	3.33	3.11	2.96
GISS	2.68	2.09	2.27	2.55	2.88	2.54	2.41	2.43	2.10	2.26	2.38	2.32
T+4,P0	2.47	2.81	2.82	1.88	2.33	3.12	3.28	2.94	2.49	2.61	2.43	2.58
T+4,P+20	2.01	2.48	2.91	2.71	2.14	3.05	3.13	2.58	2.07	2.30	2.30	2.40
T+4,P-20	2.57	2.87	2.98	2.79	2.93	3.19	3.37	3.39	3.57	3.11	2.49	2.42

Table 32. Groundwater Regime Vulnerability to Climate Change in the Väike-Maarja Study Area (VK999-C).

Model	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline	16.34	16.63	16.76	15.88	15.83	16.26	16.77	17.15	17.21	17.09	16.69	16.50
GISS	16.18	14.90	15.64	16.24	16.73	16.87	17.54	17.95	16.73	16.56	16.04	16.15
T+4,P0	15.38	15.74	15.73	14.79	15.15	16.45	17.56	18.03	18.66	18.49	16.94	16.89
T+4,P+20	13.66	14.40	15.08	15.12	14.76	15.78	16.14	16.07	14.87	14.87	15.24	15.24
T+4,P-20	15.55	16.15	16.19	15.80	15.70	15.69	15.85	16.13	16.20	15.98	15.28	14.62

Table 33. Groundwater Regime Vulnerability to Climate Change in the Öisu Study Area (VK1161).

Model	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline	1.67	1.78	1.73	1.56	1.78	1.94	1.99	1.96	1.84	1.75	1.67	1.67
GISS	1.54	1.57	1.52	1.43	1.72	1.80	2.01	1.78	1.63	1.56	1.52	1.63
CCCM	1.53	1.33	1.40	1.69	1.70	1.71	1.76	1.62	1.57	1.25	1.27	1.40
T+4,P0	1.55	1.61	1.32	1.24	1.91	1.95	2.03	1.98	2.03	1.79	1.66	1.66
T+4,P+20	1.54	1.57	1.52	1.43	1.70	1.71	1.94	1.69	1.63	1.56	1.52	1.63
T+4,P-20	1.60	1.56	1.64	1.65	1.80	1.91	1.90	2.08	2.07	2.17	2.00	2.02

Table 34. Groundwater Regime Vulnerability to Climate Change in the Piigaste Study Area (VK1165).

Model	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline	3.49	3.49	3.50	3.42	3.42	3.48	3.55	3.60	3.59	3.55	3.51	3.46
GISS	3.29	3.33	3.41	3.23	3.29	3.29	3.40	3.29	3.43	3.41	3.28	3.19
T+4,P0	3.31	3.39	3.32	3.17	3.26	3.27	3.36	3.34	3.53	3.54	3.44	3.43
T+4,P+20	3.29	3.33	3.41	3.23	3.29	3.29	3.32	3.33	3.43	3.41	3.28	3.19
T+4,P-20	3.76	3.78	3.76	3.71	3.78	3.82	3.81	3.82	3.83	3.79	3.77	3.53

Figures 6-9 express the mean annual curves of modelled groundwater levels in the studied wells. Significant changes in annual curves can be distinguished. According to the GISS scenario, the groundwater tables would rise strongly during autumn and winter. The higher level in April or in November would become the highest of the whole year in northern Estonia, instead of observed monthly maximum in May. It is caused by expected increase of precipitation during autumn and the rise of temperature in winter. In comparison to the baseline period, because of the great freezing depth, the snow meltwater, instead of infiltration into the ground, flowed into the river beds.

The spring maximum level will occur a month earlier: in March in southern Estonia and in April in the northern part of the country. Warming in winter makes the weather unstable.

Therefore sudden changes may occur in meteorological conditions as well as in groundwater regimes.

Table 35. Modelled Annual Mean Groundwater Levels in Studied Wells Using the GCM Scenarios (m from Surface)

Studied Wells	Baseline	GISS	T+4°C, P 0%	T+4°C, P +20%	T+4°C, P -20%
VK214	-3.08	-2.41	-2.65	-2.51	-2.97
Modelled Baseline	*	+0.67	+0.43	+0.57	+0.11
VK999-C	-16.59	-16.46	-16.65	-15.10	-15.76
Modelled Baseline	*	+0.13	-0.06	+1.49	+0.83
VK1165	-1.78	-1.64	-1.73	-1.62	-1.87
Modelled Baseline	*	+0.14	+0.05	+0.16	+0.09
VK1207	-3.51	-3.32	-3.36	-3.32	-3.76
Modelled Baseline	*	+0.19	+0.15	+0.19	+0.25

Groundwater Consumption and Quality in the Coastal Areas

The total amount of groundwater in the cracks and pores of Estonia's groundwater basin is nearly 2000 km³ (Vallner, 1993). One important water management problem in the coastal areas of Estonia concerns the groundwater consumption and its relation to the possible marine waters intrusions into the limestone aquifers. The limestone aquifers of the northern and central parts of the country are the fresh water reservoirs of primary importance. The waters in the Ordovician-Cambrian and Cambrian-Vendian aquifer systems are considered deep groundwaters. The average amounts of water pumped out from these aquifer systems were 31.000 and 120.000 m³ per day respectively, making up 16% of the total groundwater consumption (Groundwater ..., 1995). Due to the intense pumping, the piezometric surface of both aquifer systems has decreased considerably.

Overpumping during the last 30-40 years has created deep water-table depressions in the Cambrian and Ordovician layers. Particularly deep depressions, which are below the mean sea level, are in Tallinn and in its surroundings. Due to that, saline waters of high chlorides concentration are subjected to capillary rise, and penetrating into the wells, pollute the drinking-water.

Overexploitation is the main reason of possible salinization of the groundwater. A 1.0 m sea level rise will not have a serious impact on the groundwater quality. As the main fresh water aquifers are lying below today's sea level, the most important measures to improve the groundwater quality are: (1) developing the recharge programs, and (2) reducing pumping.

Discussion and Conclusions

The modelling results indicate that the climate change will be followed by a rise of annual mean groundwater level about 0.5 m in northern Estonia and 0.1-0.2 m. in the south. Significant changes will occur in seasonal variation of the groundwater regime. The water level in spring and autumn will rise, and floods begin earlier. The smallest water level rise is calculated by the climate change scenario of temperature increase of 4°C and precipitation decrease of 20 %. In this case the weather conditions will be less unfavourable for restoration of groundwater resources than by the other scenarios.

There is no particular need to use additional groundwater resources. In 1994 the total consumption of groundwater in Estonia was 336 mill. m³ (920.000 m³ per day). 66 % of

the above mentioned amount was pumped out from the oil shale mines. The rest was used for drinking-, agricultural and industrial water supply.

The water resources and groundwater regime analysis, using the climate change scenarios, show that the problems concerning the water resources management do not serve as a limiting factor for socio-economic development in Estonia. Natural variability of precipitation and their infiltration into the ground exceed all calculated changes caused by the climate warming.

In conclusion we can report that future dangers in the utilization of groundwater may be caused rather by negative changes in the groundwater quality than by the decrease in quantity. At the present water consumption level, the reserves of the Estonian groundwater aquifers will be sufficient enough for hundreds of years. Despite this, it is very important to address both the quantity and quality aspects to the future designs of the water supply management.

ESTONIA'S V & A ASSESSMENT FOR THE COASTAL RESOURCES SECTOR

Estonia is a seaside country, remaining entirely within the drainage area of the Baltic Sea. Due to relatively long coastline (3.794 km in total, while the territory itself is only 45.216 km²) and predominance of low-lying coastal areas (NW part of the East-European Plain), accelerated sea level rise concurrent to global climate change may strongly affect the territory of Estonia. On the other hand, location on the southern slope of the Baltic Shield which is undergoing isostatic land uplift (2.8 mm/y on the north-western coast and 1.0 mm/y in the south-west (Vallner et al., 1988) potentially reduces the effect of sea level rise (Figure 32).

**Figure 32. Scheme of Isobases of Annual Velocities of Vertical Movements (Vallner et al., 1988).
Location of Study Areas: A - Hiiumaa; B - Pärnu-Ikla; C - Matsalu Bay; D - Tallinn; E - Narva-Jõesuu-Käsmu**

Although small in area, Estonia is rich in different geomorphic types of coasts and shores. Different shore types are used by man in different way. Coastal rural settlements in Estonia are very old. Part of them have been founded over 5.000 years ago. First sheds were probably set up near the coastline. Resulted from isostatic uplift of the earth's crust, most of seaside villages are located at a distance from the coastline today. Thus, the settlements in coastal areas of Estonia, except the harbors and some certain low-lying districts of the coastal cities, are not in direct danger in the case of moderate rise of the sea.

As Estonia is relatively rich in various coastal ecosystems (reed beds, many different types of meadows including wooded meadows, dunes, cliffs etc.) which are often

valuable nesting sites for birds, and usually containing rare plant species and plant communities, much attention must be given to vulnerability and protection strategies of them.

The aim of the present study was to evaluate the impact of climate change and sea-level rise on natural systems as well as on human activities in coastal areas of Estonia. For that purpose most vulnerable to sea level rise ecosystems and human settlements were selected to assess the magnitude and quality of changes taking place in the result of above mentioned events. The present paper contains the inventory of potential losses, and the values at risk, but also some possible adaptation options and protection strategies.

Methods Used for the V&A Assessment

Sea-Level Rise Methodologies Used in the Assessment

Detailed measurements using large-scale (1:25.000) topographic and geomorphic maps and calculations according to the Bruun Rule (Bruun, 1962) were made along the coastline at 200 m intervals. There were two problems: (1) the Estonian coasts are too shoaly to apply the Bruun Rule without corrections, and (2) the overfill ratio was found quite approximately using the following coefficients:

- ☐ sand - 1.0
- ☐ silt and varved clay - 0.7
- ☐ till (loam full of shingle) - 0.4
- ☐ limestone - 0.1

It is worth mentioning that till shores in Estonia are erodible to such an extent that fine-grained fractions are washed out. The remaining shingle ridges and boulder fields prove to be extremely resistant to further erosion.

Based on measurements, calculations, and field observations, new coastline positions were drawn on the topographic maps. Field observations were used to compare possible coastline changes obtained by the Bruun Rule to existing situations, and to make corrections where necessary. Two different coastline positions were drawn, depending on either normal weather conditions or potential storm surges. Both zones were subjected to inventories of land loss and of temporary damages.

The data on water-level fluctuations and storm surges were obtained from four meteorological and sea level observation stations in Hiiumaa, from two stations on the southwestern coast, three stations on the western coast, one station in Tallinn, and from three stations on the northeastern coast of Estonia (Tables 36 a,b,c,d, and e). The data of these observation stations go back to the second half of the 1800s. Sea level fluctuations caused by tides in the Baltic Sea do not need to be taken into consideration in calculating possible coastline recession. This is due to the shallow basin and the isolation of the sea, which has a very narrow connection through the Danish Straits with the Atlantic Ocean, giving the effect of a large lake.

Finally, the data of isostatic land uplift measurements were also taken into account in land loss estimates.

Table 36a. Maximum and Minimum Sea Levels (in cm Related to the Kronstadt Benchmark) and Potential Coastline Recession (CR in m) at 1.0 m Sea Level Rise in Hiiumaa

Month	J	F	M	A	M	J	J	A	S	O	N	D	CR
Tahkuna													
max	144	135	135	126	104	104	112	118	126	138	136	153	1400
min	0	-22	-10	-6	7	20	30	30	16	5	5	8	30
Ristna													
max	112	95	95	58	47	53	55	81	89	83	86	123	100
min	-48	-63	-68	-65	-50	-40	-25	-32	-29	-53	-56	-78	30
Sõru													
max	87	73	70	51	29	43	39	51	68	73	57	84	1000
min	-57	-85	-69	-67	-44	-43	-25	-39	-34	-49	-53	-97	50
Heltermaa													
max	93	80	85	53	26	47	48	60	71	71	65	84	140
min	-54	-76	-71	-68	-50	-39	-22	-28	-24	-46	-61	-99	25

Table 36b. Maximum and Minimum Sea Levels and Potential Coastline Recession at 1.0 m Sea Level Rise on SW Coast of Estonia

Month	J	F	M	A	M	J	J	A	S	O	N	D	CR
Pärnu													
max	159	155	175	179	135	94	97	159	174	179	183	153	560
min	-107	-87	-103	-115	-85	-65	-39	-51	-61	-95	-100	-120	20
Kihnu													
max	132	150	135	68	92	59	67	94	99	118	95	127	800
min	-102	-85	-86	-86	-58	-48	-27	-47	-38	-62	-82	-133	25

Table 36c. Maximum and Minimum Sea Levels and Potential Coastline Recession at 1.0 m Sea Level Rise on W Coast of Estonia

Month	J	F	M	A	M	J	J	A	S	O	N	D	CR
Rohuküla													
max	108	79	85	83	49	69	53	79	85	95	89	107	680
min	-61	-88	-73	-73	-69	-51	-35	-35	-43	-66	-75	-101	30
Keemu													
max	91	57	66	95	50	115	60	93	123	127	157	95	6400
min	-68	-71	-49	-66	-56	-51	-17	-32	-48	-62	-49	-53	30
Virtsu													
max	118	102	113	54	65	68	58	87	119	104	106	114	1000
min	-80	-95	-77	-84	-66	-50	-41	-56	-46	-67	-81	-112	20

Table 36d. Maximum and Minimum Sea Levels and Potential Coastline Recession at 1.0 m Sea Level Rise in Tallinn

Month	J	F	M	A	M	J	J	A	S	O	N	D	CR
max	101	108	107	84	49	55	53	73	119	100	105	113	1000
min	-81	-84	-84	-81	-55	-66	-46	-49	-52	-64	-74	-95	5

Table 36e. Maximum and Minimum Sea Levels and Potential Coastline Recession at 1.0 m Sea Level Rise on NE Coast of Estonia

Month	J	F	M	A	M	J	J	A	S	O	N	D	CR
Loksa													
max	91	81	105	89	45	57	49	71	117	87	101	123	50
min	-95	-87	-70	-89	-69	-53	-33	-35	-55	-75	-83	-89	10
Kunda													
max	109	79	92	70	60	60	83	81	100	107	113	118	140
min	-76	-91	-85	-71	-59	-45	-36	-51	-40	-69	-82	-93	25
Narva-Jõesuu													
max	132	113	134	117	88	132	88	106	202	158	164	142	130
min	-141	-98	-85	-86	-60	-75	-67	-77	-60	-92	-113	-97	25

Selection of Study Sites

Estonia is rich in different geomorphic types of coasts (Figure 33). The contemporary coast of the country is primarily made of shoals. The shoal coast can be subdivided into low and bluff shores. According to the tilt of the primary relief, geological character of initial rocks, and prevailing shore processes, eight shore types have been distinguished by Orviku (1992): cliff shore, scarp shore, rocky shore, till shore, gravel shore, sandy shore, silty shore, and artificial shore.

Figure 33. Distribution of Coastal Types (Orviku, 1992). 1 - straightening abrasion-accumulation embayed coast in Quaternary deposits, 2 - straightening abrasion-accumulation embayed coast in Pre-Quaternary bedrock, 3 - straightened abrasion-accumulation coast, 4 - straightened abrasion coast, 5 - straightened accumulation coast

All the shore types listed may display a variety of natural patterns according to which stage of development they have reached, which depends on their exposure to prevailing currents, the time of exposure, and several other factors (Orviku, Sepp, 1972).

Five study areas containing all eight shore types were selected to assess Estonia's vulnerability to sea level rise. These are: (1) Hiiumaa; (2) Pärnu-Ikla; (3) Matsalu Bay; (4) Tallinn; and (5) Narva-Jõesuu-Käsmu. Hiiumaa is the second largest island of the West Estonian Archipelago, which represents a variety of geomorphic coast and shore types characteristic of the whole archipelago. The other four study areas are situated in different parts of the mainland, and each represents two or three predominant shore types: Pärnu-Ikla has sandy and till shores, Matsalu Bay has silty, till and rocky shores, Tallinn has scarp, sandy and artificial shores, and Narva-Jõesuu-Käsmu - cliff, sandy and till shores.

Hiiumaa (989 km²) is located in the northern part of the West Estonian Archipelago, and is surrounded by nearly 200 islets. It is a low-lying island; most of the land is between 1 m and 10 m above sea level. The highest point on the Kõpu Peninsula (68 m) is the exception. The coastline (326 km) is fairly straight along the western and eastern shores. Peninsulas and bays are more characteristic along the northwestern and southeastern shores. The primary shore types on the island are (1) beaches with coastal ridges and dunes, (2) gravel shores with coastal ridges, (3) abraded till shores with occasional boulders, (4) silty shores surrounding shallow bays, and (5) low limestone shores. The only city, Kärdla, and the harbors have artificial shores with protective construction. Because of its insular position, small area, and low population (10.600 inhabitants), the island has no particular economic significance. The primary fields of human activity are agriculture, fisheries, forestry, and tourism.

Pärnu-Ikla study area is located in southwestern Estonia on the western coast of the Gulf of Riga. The area includes two small populated isles - Kihnu and Manilaid. The

coastline (150 km) is fairly straight. Most of the area is made up of sandy beaches with an extensive ridge of coastal formations covered by foredunes and dunes. The highest dunes of Estonia (40 m above sea level) are situated in its southern part. This is one of the most popular recreation areas in the country, with famous health resorts in Pärnu and numerous motels between Rannametsa and Ikla.

Matsalu Bay study area running from Virtsu (in the south) to Haapsalu (in the north) embraces the most characteristic shore types of the West Estonian Plain. Its coastline length is 230 km. The central part of the study area, which surrounds the Matsalu Bay, is made up of very low-lying varved clay plain with silty shores covered by reed beds, coastal, and flood plain meadows. It is one of the most important wetlands of Estonia, being a part of the Matsalu Nature Reserve. The southern and northern parts of the area have mainly abraded till shores with erratic boulders. Some limited sections of the coast near Virtsu have rocky shores. Haapsalu is famous for curative mud and health resorts.

Tallinn is the capital and the largest city of Estonia. The study area from the Tiskre brook mouth in the west to the Cape of Miiðuranna in the northeast has a 67 km long coastline, which is indented by numerous peninsulas and bays. The primary shore types are: scarp, till and sandy shores. As Tallinn is main harbor of Estonia, it has relatively long artificial shores with protective constructions.

Narva-Jõesuu-Käsmu study area is located in northeastern Estonia on the southern coast of the Gulf of Finland. The coastline (190 km) is very straight in the east, and more indented by peninsulas and bays in the west. Most of the area consists of the

Baltic Glint, a high (up to 56 m above sea level) limestone cliff, which separates the North Estonian Coastal Plain from the Harju-Viru Limestone Plateau. The glint is divided into the glint headlands and glint bays. The North Estonian Coastal Plain, which lies between the glint and the sea, is a differentiated area, with peninsulas and headlands stretching far into the sea, and with bays between them. In the places of the glint headlands, cliff shore type is predominant. In the areas where coastal plain is wider, abraded till shores with boulders and sandy shores with coastal ridges and dunes are characteristic.

Methodology for Economic Analyses

All the potentially lost values of inundation and storm surge zones are calculated proceeding from the current average prices in Estonia. Three different types of losses were accounted in monetary values: (1) cost of submerged and temporarily damaged land; (2) cost of really existing properties in these two zones today; and (3) profit, theoretically missed from the damaged meadows and forests.

The overall price of potentially lost values for the whole coastal zone of Estonia was calculated by multiplying the prices of study areas by four (the coastline length of the study areas provides 25% of the total coastline length of Estonia), and adding the prices of losses in the coastal cities.

Adaptation Alternatives Evaluated Using the Methodology

Main adaptation options, which were assessed to protect valuable coastal territories and constructions were the following: (1) constructing of seawalls, (2) hardening of

headlands; and (3) beach nourishment. Constructing of seawalls and beach nourishment are well known techniques, and have widely discussed in the context of sea level rise (Nicholls et al., 1995). It is obvious that the cities at risk need to be protected by seawalls and dikes. Most of the harbors need upgrading. The sandy beaches of high recreational value can be saved by the means of beach nourishment, the technique which have been successfully applied already in Narva-Jõesuu. Unique ecosystems of great scientific value could be protected by hardening of headlands.

Results and Discussion of the V&A Assessment

The results of the Estonia's vulnerability assessment to 1.0 m sea level rise in 2075 were obtained. A 0.3 m scenario would not have a noticeable effect because of the isostatic land uplift.

Land Loss Analysis Results

According to the data obtained from four meteorological and sea level observation stations in Hiiumaa, the highest sea levels have been measured at the stations most exposed to waves and storm surges, reaching 1.53 m above the Kronstadt 0 (local benchmark for the eastern part of the Baltic Sea) in Tahkuna (Table 36a). At the same time sea level fluctuations are more considerable on the eastern and southern coasts of the island, probably due to the shoals.

Although a slow uplift of the earth's crust is occurring in Hiiumaa today (Vallner et al., 1988), there has been erosion of sandy beaches in recent decades, and in some places the sea is advancing again (Orviku, 1987).

Since 1954, the whole West Estonian Archipelago has been subject to at least eight (in 1954, 1967, 1969, 1971, 1975, 1983, 1986, 1990) extremely strong storms that, according to statistics, should occur only once in 100 years. In autumn and winter, the westerly and southwesterly storm winds raise the sea level up to 2.0 m above its summer level. As there is little evidence of a rising sea level in Estonia over this period, beach erosion appears to be largely due to the recent increased storminess in the eastern Baltic Sea.

Measurements and calculations indicate that the shore types most vulnerable to sea level rise are sandy shoal and silt shores. Sandy beaches are concentrated on the western coast of Hiiumaa, while silt shores prevail in the northwest and southeast. Under a 1.0 m sea level rise scenario, the most extensive coastline recession (1.400 m) would occur on the silt shores near Kõrgessaare and Käina (Figure 34).

Figure 34. Affected by 1.0 m Sea Level Rise Area in Hiiumaa. 1 - Inundation Zone; 2 - Storm Surge Zone

A 1.0 m sea level rise would inundate 38 km² of the coastal area of Hiiumaa. Additionally, 155 low-lying islets off the coast of Hiiumaa would disappear, and 43 new islets would be created by separation from current headlands. A number of valuable coastal ecosystems, plant communities, and rare plant species would be

destroyed. Some of them are located within the limits of the West Estonian Biosphere Reserve, which is a valuable breeding ground for birds.

The estimates of losses indicate that 100% of reed beds and 80% of coastal meadows (salt marshes), including rare saline plant communities of *Salicornia europaea* and *Carex glareosa*, and *Glaux maritima-Juncus gerardi* plant community which is found here in all successional transitions, are in direct danger. In addition, biotopes of several unique plant species would also be affected (Table 37). Protected area of *Alnus glutinosa* stand in Luidja would be at risk.

The very unusual ecosystems of numerous lagoons and calcareous meadows rich in orchids on the northwestern coast of Hiiumaa would completely disappear. The same would happen to the spawning grounds for trouts and lavarets.

Because the villages on the island are usually situated at a distance from the coastline, only a few dwellings are situated in inundation zone. Potential losses and their approximate monetary values are given in Tables 38, 39, and 40.

For the Pärnu-Ikla study area, coastal measurements and calculations using the Bruun Rule indicate that the areas most vulnerable to sea level rise are located in the northern part, where silt shores are predominant, but also on the densely populated Isle of Kihnu. Coastal formations that act as protection against inundation are located at a distance from today's coastline. Dikes built before the last world war are no longer effective. During the most recent strong storms, the waves have reached many dwellings 300 m inland. Where ridges of coastal formations are interrupted by brook

Table 37. Biotopes of Rare Plant Species in Inundation Zone

Plant Species	Hiiumaa	Matsalu Bay	Narva-Jõesuu-Käsmu
<i>Allium vineale</i>	x		
<i>Armeria elongata</i>		x	
<i>Artemisia rupestris</i>		x	
<i>Astragalus arenarius</i>			x
<i>Berula erecta</i>	x		
<i>Butomus umbellatus</i>	x		
<i>Carex davalliana</i>		x	
<i>Carex mackenziei</i>		x	
<i>Coeloglossum viride</i>	x	x	
<i>Crambe maritima</i>	x		
<i>Cypripedium calceolus</i>			x
<i>Dactylorhiza baltica</i>		x	
<i>Dactylorhiza cruenta</i>		x	
<i>Dactylorhiza Ruthei</i>		x	
<i>Daphne mezereum</i>			x
<i>Elymus junceiformis</i>	x		
<i>Epipactis atrorubens</i>		x	x
<i>Epipactis helleborine</i>		x	
<i>Eryngium maritimum</i>	x		
<i>Festuca sabulosa</i>	x		
<i>Gladiolus imbricatus</i>		x	
<i>Halimione pedunculata</i>	x		
<i>Hermannium monorchis</i>	x	x	x
<i>Iris sibirica</i>		x	
<i>Lathyrus maritimus</i>	x		x
<i>Limosella aquatica</i>	x		
<i>Listera cordata</i>		x	
<i>Melilotus dentatus</i>		x	
<i>Moehringia lateriflora</i>			x
<i>Myosotis laxa</i>	x		
<i>Myrica gale</i>		x	
<i>Nuphar luteum</i>	x		
<i>Ophrys insectifera</i>		x	
<i>Orchis mascula</i>		x	
<i>Orchis militaris</i>		x	x
<i>Orchis ustulata</i>			x
<i>Petassites spurius</i>	x		
<i>Poa alpina</i>		x	
<i>Polygonum oxyspermum</i>	x	x	
<i>Pulsatilla pratensis</i>			x
<i>Rhynchospora fusca</i>			x
<i>Sagina maritima</i>	x		
<i>Salsola kali</i>	x		
<i>Samolus valerandi</i>	x		
<i>Silene viscosa</i>			x
<i>Suaeda maritima</i>	x		
<i>Tetragonolobus maritimus</i>		x	

valleys or drainages, low-lying meadows beyond the ridges and dunes are also vulnerable to being inundated, and when the seas are high, dunes are being eroded.

A 1.0 m sea level rise would inundate 22.2 km² of coastal territory (Figure 35; Tables 38, 39, and 40). Almost 2.5 km² of the territory of Pärnu, the largest city in this region, and 3.8 km² of the Isle of Kihnu are located in the zone of inundation. The potential reduction of the effects of sea level rise by isostatic land uplift here (about 1.0 mm/year) is less than in Hiiumaa. That is why the potential land loss compared with that in Hiiumaa is relatively much greater (the coastline length is only 150 km compared to a coastline length of 326 km in Hiiumaa). One small and low islet existing today would submerge, and the 5.0 m high Piklanina headlands would become an islet. The data of long-term sea level observations show that maximum storm surges elevate the sea level by 1.83 m in Pärnu and 1.50 m on the Isle of Kihnu. It is obvious that any increase in sea level will increase the height and landward penetration of surges. Pärnu and Kihnu are at particular risk in that respect.

Figure 35. Affected by 1.0 m Sea Level Rise Area in Pärnu-Ikla Study Area. 1 - Inundation Zone; 2 - Storm Surge Zone

Finally, extensive coastal meadows which were used as valuable pastures not long time ago, are overgrown with reed by now, and do not provide any significance from biodiversity aspect. There are no rare or highly valuable natural ecosystems in the Pärnu-Ikla area that would need special protection today. The primary problems here are the socioeconomic impacts and particularly, the protection of recreational areas.

The Matsalu Bay study area is the most vulnerable to sea level rise in Estonia. Its central part, embracing the Kasari flood plain and the Matsalu reed bed, is particularly low and flat, being 1-2 m above sea level. A 1.0 m sea level rise would inundate 76.6

km² of the territory (Table 38) including the whole reed bed and most of the flooded meadows. The coastline recession here is the longest (6.4 km) in Estonia (Figure 36).

Table 38. Economic Vulnerability (in USD) of the Study Areas to 1.0 m Sea Level Rise
Inundation zone

	HIUMAA		MATSALU BAY		PÄRNU-IKLA		NARVA-JÕESUU-KÄSMU	
Territories and Constructions	Losses	Values in USD	Losses	Values in USD	Losses	Values in USD	Losses	Values in USD
Coastline Length (km)	326		230		150		190	
Coastal Meadows (km ²)	7.8	135.265	31.0	832.867	19.7	479.859	0.86	25.956
Beaches (km ²)	5.6	97.113	0.15	4.030	1.4	33.858	2.9	87.527
Wetlands (km ²)	13.7	237.581	38.0	1.020.933	0.8	19.487	3.3	99.600
Forests (km ²)	8.3	143.936	7.5	201.500	0.3	7.308	1.54	46.480
Settlements (km ²)	2.6	45.088	-	-	-	-	0.11	137.500
Total Area (km ²)	38.0	658.983	76.6	2.059.330	22.2	540.511	9.8	397.064
Timber (m ³)	126.990	5.291.250	114.750	4.781.250	4.590	191.250	23.562	981.750
Hay (in 100 kg/80 years)	561.600	3.510.000	2.232.000	13.950.000	1.418.400	8.865.000	133.920	837.000
Dwellings	20	9.167	27	123.750	30	137.500	120	550.000
Sheds	60	5.000	30	2.500	60	5.000	-	-
Harbors	7	all possible damages can be avoided by regular care	2	all possible damages can be avoided by regular care	-	-	5	all possible damages can be avoided by regular care
Beacons	8		1		-	-	5	
Roads (km)	9.65	482.500	12	600.000	-	-	8.5	425.000
Overhead Lines (km)	15.5	90.417	7.3	42.583	-	-	11.8	68.833
TOTAL		10.129.750		21.559.413		9.739.270		3.259.647

Both reed beds and flooded meadows are very dynamic plant communities having a number of successional transitions between different site types depending on

Table 39. Economic Vulnerability (in USD) of the Study Areas to 1.0 m Sea Level Rise

Storm surge zone

	HIUMAA		MATSALU BAY		PÄRNU-IKLA		NARVA-JÕESUU-KÄSMU	
Coastal Meadows (km ²)	30	51.917	23	617.933	20.2	492.038	0.7	20.277
Wetlands (km ²)	-	-	15	403.000	-	-	3.7	107.177
Forests (km ²)	44.2	7.665.017	25.5	685.100	2.45	59.678	2.5	72.417
Arable Lands (km ²)	-	-	4.5	120.900	-	-	0.03	869
Settlements (km ²)	1.1	1.100.000	-	-	-	-	0.2	350.000
Total Area (km ²)	75.3	9.285.267	68.0	1.826.933	22.65	551.716	7.15	550.739
Timber (m ³)	676.260	28.177.500	390.150	16.256.250	37.485	1.561.875	382.500	1.593.7500
Hay (100 kg/80 years)	2.160.000	13.500.000	1.656.000	10.350.000	1.454.400	9.090.000	161.280	1.008.000
Dwellings	330	1.512.500	267	1.223.750	304	1.393.333	415	1.902.000
Sheds	220	18.333	120	10.000	211	17.583	-	-
Roads (km)	44	2.200.000	40	2.000.000	0.7	35.000	31.4	1.570.000
Overhead Lines (km)	60	350.000	36	210.000	-	-	22.4	130.750
TOTAL		55.043.600		31.876.933		12.649.500		21.099.070

hydrologic regime and climatic fluctuations. Flooded meadows of the Kasari River are remarkable on the all-European background because of their extensive massif, worth preserving. The Matsalu reed bed (about 3 000 ha) is the biggest and most important

breeding ground for birds in Estonia. Coastal meadows in natural conditions as well as flooded meadows and reed beds are temporarily flooded. That is why they will move landwards, but will not be destructed. Despite this, a 1.0 m sea level rise would

Figure 36. Affected by 1.0 m Sea Level Rise Territory in the Matsalu Bay Study Area. 1 - Inundation Zone; 2 - Storm Surge Zone

Table 40. Economic Vulnerability (in USD) of the Studied Cities to 1.0 m Sea Level Rise

Inundation Zone

	TALLINN		PÄRNU		HAAPSALU	
Territory	3.34	22 267. 000	2.45	5.512.500	0.82	1.100. 000
Housing stock	57	2. 917. 000	275	6. 875. 000	32	400. 000
Enterprises	7	583. 333	-	-	-	-
Streets (km)	7.7	770. 000	13.0	1.300. 000	4.5	4.500
TOTAL		26. 536. 666		13. 687. 500		1. 414. 500

Storm Surge Zone

Territory (km2)	3.04	20. 266. 666	1.95	4. 387. 500	0.54	720. 000
Housing stock	162	26. 333	650	16. 250. 000	348	4.350. 000
Enterprises	181	14. 166. 666	-	-	-	-
Streets (km)	16.1	1. 610. 000	32.0	3. 200. 000	7.6	760. 000
Railroads (km)	8.3	?			1.2	?
TOTAL		62. 377. 416		23. 837. 500		5.830. 000

decrease their species richness because the new sites for developing seashore grasslands are mostly arable lands or young species-poor forests, and many of the rare species may not survive migration to these unfavourable sites. All the other plant

communities such as wooded meadows, deciduous forests, dry calcareous grasslands, calcareous paludifying grasslands, alvar (thin-soil calcareous) forests, alvar grasslands, and fen grasslands would not be much affected.

Considerable changes would take place near Virtsu, an important port connecting the mainland with Saaremaa and Muhu Island. Virtsu is situated on a peninsula, which in the case of 1.0 m sea level rise would turn into many islets. Several plant communities and biotopes of rare species, including unique species of orchids, would disappear. At the same time new wetlands would be created in the result of elevated groundwater tables, being suitable biotopes for many other orchids.

The main hazard of the rising sea would appear in combination with the modern land use. Today, natural and seminatural communities are located more often near the shoreline, while cultivated communities and overgrown lands occur inland. Sea level rise would restore approximately the same coastline position as it was in the 1700s. Consequently, all plant communities would relocate inland. Unlike the situation in the 1700s, there are arable lands, secondary species poor forests, and cultivated grasslands, which prohibit further shifts of natural and seminatural communities today. The lack of suitable species pool in new sites, and unfavourableness of new conditions for migrating grassland species will probably result in a considerable decrease in species richness.

The Tallinn study area embraces the whole coastal territory of the capital city. Although 1/3 of the city's coastline is protected by dikes, the possible damages in Tallinn would be the greatest compared to the other four study areas. The most

vulnerable is the plane and non-protected northwestern part of the city (Kopli, Paljassaare Peninsula, Hundipea and Kalamaja districts). The Paljassaare Peninsula, which provides over half of potentially submerged area of Tallinn, has no significance as a dwelling district. Most of damages here come from the land loss. The losses in the storm surge zone would be much more significant. About 160 dwellings and 180 industrial buildings near the shoreline would be damaged by the storm flood.

The Narva-Jõesuu-Käsmu study area is very diverse in morphology, geological structure, and shore types. It is extremely narrow (0-10 m) between straight and compact sections of the Baltic Glint and the sea. Most of the cliff shores here would not be much affected by sea level rise. In the areas where the glint bays are facing peninsulas which stretch far into the sea, the coastal plain may widen up to 15-20 km, for instance in Lahemaa National Park. Such extensions of the coastal plain are more populated and more vulnerable to sea level rise.

Measurements and calculations according to the Bruun Rule indicate that only 9.8 km² of the territory would be lost at 1.0 m sea level rise (Tables 38 and 39). The long-term observation data show that the biggest fluctuations of the sea are characteristic to the easternmost part of the area (Table 36e). The difference between maximum (+202 cm) and minimum (-141 cm) sea levels in Narva-Jõesuu is nearly 3.5 m.

The easternmost part of the study area between Narva-Jõesuu and Meriküla is one of the most suitable areas for recreation in Estonia. But the excellent sandy beaches here have suffered from strong storms in recent decades. Most probably, one of the reasons

of severe damage is that the runoff of the Narva River dropped drastically after the hydroelectric power plant was built on the river and the reservoir was dammed up in 1956. Earlier, the high flow rate of the Narva River had restrained the damaging effect of currents and waves on the beach. Formerly, the river also carried larger amounts of sand to its mouth, which settled at the place where the river flow and sea currents crossed. As the accumulating and buffering effect of the Narva River has essentially decreased, storms have full liberty to carry coastal sediments eastwards. Consequently, a 1.0 m sea level rise, combined with higher storm surges, would damage the beach very seriously.

The other site of great risk in the study area is Sillamäe, an important industrial centre. The dumping site of the former uranium enrichment plant at Sillamäe is still the greatest threat to the environment of the coastal plain and the Gulf of Finland. It is isolated from the sea by a narrow dam. Every year thousands tonnes of radioactive substances containing ^{238}U , ^{232}Th , and ^{226}Ra leak into the soil and sea from here. Sea level rise and stronger storms would increase the risk of breaking down the dam and causing catastrophic pollution of the sea.

Aggregate Assessment Results

The estimates of potential losses over all coastal territory of Estonia are based on the results of the study areas. As the total coastline length of four study areas (without Tallinn), being 900 km, provides nearly 25% of the coastline length of the whole

country, the overall price was calculated by multiplying the total price of the study areas by four, and adding the total price of the studied cities (Table 41).

Table 41. Aggregate Economic Vulnerability (in USD) of Estonia to 1.0 m Sea Level Rise

	Inundation Zone	Storm Surge Zone	Both Zones Together
Hiiumaa	10.129.750	55.043.600	65.173.350
Pärnu-Ikla	9.739.260	12.649.500	22.388.760
Matsalu Bay	21.559.415	31.876.930	53.436.345
Narva-Jõesuu-Käsmu	3.259.650	21.099.070	24.358.720
Estonia in Total without Cities	44.688.075 x 4 = 178.752.300	120.669.100 x 4 = 482.676.400	165.357.175 x 4 = 661.428.700
Studied Cities	41.638.670	92.044.915	133.683.585
Total	220390.970	574.721.315	795.112.285

Adaptation Options

Coastal land loss can be prevented mainly by beach nourishment and constructing seawalls. The cities at risk such as Tallinn, Pärnu, and Haapsalu, but also Kuressaare, Kärđla, Sillamäe, and Narva-Jõesuu would need to be protected by seawalls and dikes. To ensure effective protection, the seawalls must be much longer than the coastline length expected to protect. These constructions are very expensive, sometimes exceeding the cost of potential losses. According to the current prices in Estonia, construction of a 2.5 m high and 4.5 m wide seawall with a seaward slope of 1:2 and landward slope 1:6 - 1:8 would cost about 15.000 Estonian Kronas (1.250 USD) per every 1 m of length. For example, protection of the total coastline of Tallinn by such a seawall would cost approximately 75 mill. U.S. Dollars. If to take into account possible storm floods, when the water level may rise up 1.5 m, the seawall should be at

least 4 m high. In this case, the cost of protection would be 100 mill. U.S. Dollars. At the same time the estimated damage due to land loss and storm surge makes up 89 mill. U.S. Dollars. For Pärnu, the respective figures are 37.5 mill. (due to losses) and 16.5 mill. U.S. Dollars (for protection). Constructing of seawalls will be one reasonable option to prevent socioeconomic hazards in the cities.

As for the West Estonian Archipelago and the West Estonian Plain, the most useful adaptation option to preserve unique and valuable natural ecosystems would be hardening of headlands to avoid the coastline straightning. This method can be applied in the areas where we have nothing to loose on the shores of the bays behind the headlands. Hardening of headlands will result in much stronger erosion in the bays.

Finally, the sandy beaches of Estonia need to be protected by beach nourishment, the technique which has been applied in Narva-Jõesuu already. The same adaptation option would be needed also in the western part of Hiiumaa, southwestern part of Saaremaa, southern part of the Pärnu-Ikla study area, and in limited sections of the northern coast of Estonia. In general, based on approximate calculations, there are only some limited areas where the cost of beach nourishment would not exceed the expected profit from recreation and tourism.

Conclusions

The present analysis makes possible to conclude that the average sea level rise of 1.0 m would result in considerable changes in coastal ecosystems, and lead to remarkable economic hazards. In particular, different regions of Estonia would suffer from

different reasons. Increasing erosion and changes in sedimentation regime would cause serious disturbance in the areas of sandy beaches and dunes, particularly in southwestern and northeastern Estonia. In addition, vanishing of sandy beaches will have negative impact on recreation. In the western part of Estonia (including large islands) the direct destruction of the coast will not be so strong, but the interaction of changing water level and land use would cause a decrease in biodiversity. Seashore plant and animal communities would relocate landwards. Moreover, inundation of one of the most important objects of nature conservation in Estonia - the Kasari flooded meadow in Matsalu Nature Reserve as a well known breeding ground for many rare bird species - would have negative influence not only on many local bird populations, but also on populations of migrating birds species of all Europe. The economic hazards will be the highest in the surroundings of Tallinn where the roads, houses and other constructions are often very close to the present shoreline. Saltwater intrusions, in general, would not provide a problem for Estonia. Freshwater consumption by the people do not depend on the upper layers of the groundwater. Drinking water is usually pumped up from very deep aquifers of the Vendian, Ordovician and Silurian sedimentary rocks, which would not be affected by sea level rise and saltwater intrusions. The only problem would come from salinization of coastal soils and plant communities.

INTEGRATION ACROSS SECTORS AND ASSESSMENT OF RELATIVE VULNERABILITY

The current study concentrates on the influence of global climate change on four main socio-economic sectors: agriculture, forestry, water resources, and coastal resources.

The impact of a 1.0 m sea level rise on the economy of Estonia is also taken into account. The future forecasts do not include the shifts in economy caused by socio-political changes(membership of EC) and the possible shifts in migration due to the climate change. All the studies are based on the present socio-economic structure influenced by the future climate change.

Global climate change will have the most significant effect on agriculture, forestry, and coastal resources. The changes in agriculture will accordingly influence the whole structure of Estonian economy. In the assessment of Estonian agriculture the emphasis was laid on the cultivation of crops. The results showed that due to the climate change the barley yield decreased 17-18% and the potato yield became unstable. The weather conditions were more favourable only for herbage cultivation.

The total effect of the climate change is probably not damaging to agriculture. Moderate rise of temperature and stability of moisture will favour agricultural production, although some restructuring activities will be needed: breeding new cultivars as well as changes in planting dates, fertilization, irrigation, and land usage. An increase in the biomass of grasslands and more mild winters will result in the development of

dairy-farming, which in its turn would support the production of one of the traditional export articles - foodstuffs.

The effects of the climate change on Estonian forest resources can't be defined so accurately. A summary of the different sample plots shows that the total biomass of forests may decrease 21-35%. The migration of species was not taken into account in the models used in this study. A logical consequence of the climate warming would be the replacement of the present species in forest ecosystems by those of more southern distribution. In this case the results of productivity and economic assessment could be completely different.

The total economic loss because of the sea level rise would be considerable, especially in the storm surge zone. A 1.0 m sea level rise would risk several natural values, but would not cause particular mobility of the population because of relatively sparse settlements and low density of population in the coastal zone. As a result of the sea level rise scenario, about 3% of the territory of Estonia would be inundated or temporarily damaged. As the economic losses are distributed between different owners and take place during a comparatively long period, the activities to protect the seashore are unrealistic in general. The exceptions could be the seaside cities and some beaches of high recreational value.

The climate warming would not cause any problems with water supply. The results of water supply and demand analysis indicate that possible climate change has no particular effect on water management in Estonia. The positive effect may be in lower

energy consumption because of milder winters, but also in better navigation conditions because of longer ice free periods in our harbors.

Climate warming will probably cause some changes in the life style and cultural habits (no snow any more), but the shifts because of temperature rise will be less important than those because of cultural contacts.

Finally, we can conclude that the climate change will not have catastrophic effect on Estonian economy. Vice versa, the summary of changes will be even favourable from the economic point of view. It will increase the producers (food manufacturing) surplus and decrease the consumers (heating) surplus in Estonia.

ACKNOWLEDGEMENTS

We would like to thank the U.S. Country Studies Management Team for giving us the possibility to participate in the Global Climate Change Project, and for valuable advice in preparing the Estonian National Report on V&A Assessment. We are also grateful to Dr. Rein Viiralt from the Estonian Agriculture University and Dr. Taavet Valgus from the Estonian Research Institute of Agriculture for contributing to the agriculture sector of the present report. Professor Martin Zobel from the Institute of Botany and Ecology of the University of Tartu, Dr. Urve Ratas and Ms. Elle Puurmann from the Institute of Ecology, and Dr. Kaarel Orviku from the Joint-Stock Company "Merin" have deserved our greatest respect for contributing to analytical phase of the study in the forestry and coastal resources sectors, and for helpful comments and advice.

REFERENCES

- Berglund, B.E. (ed.). 1986. *Handbook of Holocene Palaeoecology and Palaeohydrology*. New York: John Wiley & Sons, 869 pp.
- Birks, H.J.B. 1981. The Use of Pollen Analysis in the Reconstruction of Past Climate: A Review. In: Wigley, T. et al. (eds.): *Climate and History*. Cambridge Univ. Press, Cambridge, Great Britain, 111-138.
- Botkin, D.B., Janak, J.F., and J.R. Wallis. 1972. Some Ecological Consequences of a Computer Model of Forest Growth. *Journal of Ecology*, 60: 849-873.
- Bruun, P. 1962. Sea Level Rise as a Cause of Shore Erosion. *Journal of Waterway, Port, Coastal and Ocean Engineering*, ASCE, 88: 117-130.
- Chambers, F.M. (ed.). 1993. *Climate Change and Human Impact on the Landscapes*. London, Great Britain: Chapman & Hall, 303 pp.
- Delcourt, H.R. and P.A. Delcourt. 1988. Quaternary Landscape Ecology: Relevant Scales in Space and Time. *Landscape Ecology*, 2: 23-44.
- Ellenberg, H. 1982. *Vegetation Mitteleuropas mit den Alpen in Ökologischer Sicht*. Stuttgart, Germany: E. Ulmer, 989 pp.

Elmet, H., Oll, Ü., and H. Roostalu. 1995. Natural and Economic Preconditions for Development of Sustainable Agriculture in Estonia. *Abstracts of the 2th International Conference of Agricultural Scientists from the Nordic and Baltic Countries*. Tartu, Estonia, 50 pp.

FAO/UNESCO. 1994. Soil Map of the World, 1: 5.000.000: Revised Legend. ISRIC, Wageningen, Netherlands, 140 pp.

Groundwater. 1995. *Groundwater State in 1994*. Geological Survey of Estonia. Tallinn, Estonia, 151 pp.

Guiot, J., Harrison, S.P., and I.C. Prentice. 1993. Reconstruction of Holocene Precipitation Patterns in Europe Using Pollen and Lake-Level Data. *Quaternary Research*, 40: 139-149.

Holdridge, L.R. 1967. *Life Zone Ecology*. Tropical Science f. San Jose, Costa Rica.

Hulten, E. 1950. *Atlas for Distribution of Vascular Plants in North-Western Europe*. Stockholm, Sweden: AB Kartografiska Institutet, 512 pp.

Huntley, B. and I.C. Prentice. 1988. July Temperatures in Europe from Pollen Data 6.000 Years Before Present. *Science*, 241: 687-690.

Jelovicheva, J., Bogdel, I., Zernitskaya, V., and V. Klimanov. 1988. Climate Reconstruction by Pollen Data. In: *Palaeoclimate During the Holocene in the Territory of USSR. Moscow, USSR: Institute of Geography*, 86-103.

Jürisson, I. and L. Raave. 1984. Influence of Climatic Conditions on Grass Production and Quality. In: *The Impact of Climate on Grass Production and Quality: Proceedings of the 10th General Meeting of the European Grassland Federation in Norway*, 95-99.

Kalda, A. 1995. Broad-Leaved Deciduous Forests in Estonia. In: *Consortium Masingii. Tartu, Estonia: Tartu University*, 89-96.

Karoles, K., Leemet, A., and O. Lugas. 1994. *Forest and Forest Product Country Profile. Estonia. United Nations, New York, Geneva*, 62 pp.

Kask, M. and L. Laasimer. 1975. Botanical Characterization of the Excursion Route in the Estonian SSR. In: *Some aspects of Botanical Research in the Estonian SSR. Tartu, Estonia: Estonian Academy of Sciences*, 7-26.

Kellomäki, S. and M. Kolström. 1992. Simulation of Tree Species Composition and Organic Matter Accumulation in Finnish Boreal Forests under Changing Climatic Conditions. *Vegetatio*, 102: 47-68.

Kellomäki, S., Hänninen, H., and T. Kolström. 1988. Model Computations on the Impacts of the Climate Change on the Productivity and Silvicultural Management of the Forest Ecosystem. *Silva Fennica*, 22: 293-305.

Kessel, H. and J.M. Punning. 1984. The Development of the Baltic Sea in the Holocene. In: *Estonia: Nature, Man Economy*. Tallinn, Estonia: Estonian Geographical Society, 36-47.

Kitse, E. and H. Roostalu. 1970. Dependence of the Potato Yield on Meteorological Conditions. *Transactions of the Estonian Agricultural Academy* (Tartu, Estonia), 69: 133-158 (in Russian).

Klimanov, V. 1987. About Climatic Changes in the Northern Part of the East-European Plain. *Palaeohydrology of the Temperate Zone III, Mires and Lakes*. Acad. Sci. Estonian SSR, Inst. Geol., 23-37.

Klimanov, V., Koff, T., and J.M. Punning. 1986. Climatostratigraphic Study of Subatlantic Sediments in the Nigula Bog (SW Estonia) and Reconstruction of Palaeoclimatic Conditions by Pollen Data. In: *Isotope-Geochemical Studies in Baltic Countries and Byelorussia*. Tallinn, Estonia, 117-129 (in Russian).

Koff, T. 1992. Palynological Studies of Estonian Holocene. *Publications of Karelian Institute* (University of Joensuu, Joensuu, Finland), 102: 75-83.

Laasi, E. 1967. *Dendrology*. Tallinn, Estonia: Valgus, 671 pp. (in Estonian).

Laasimer, L. 1965. *Vegetation of the Estonian SSR*. Tallinn, Estonia: Valgus, 397 pp. (in Estonian).

Lõhmus, E. 1984. *Estonian Types of Forest Habitat*. Tallinn, Estonia. 88 pp. (in Estonian).

) Nicholls, R.J., Leatherman, S.P., Dennis, K.C., and C.R. Volonte. 1995. Impacts and Responses to Sea-Level Rise: Qualitative and Quantitative Assessments. In: Nicholls, R.J. and S.P. Leatherman (eds.): *Journal of Coastal Research: Special Issue*, 14. The Coastal Education and Research Foundation, 26-43.

Older, H., Viiralt, R., Laidna, T., Parol, A., and A. Selge. 1994. Recent White Clover Research and Development in Estonia. *Herba*, 7: 35-40.

Orviku, K. 1987. Estonian Seashore and Their Dynamics. *Eesti Loodus*, 11: 712-719 (in Estonian).

Orviku, K. 1992. Characterization and Evolution of Estonian Seashores. Tartu, Estonia: Summary of Doctoral Thesis at Tartu University, 20 pp.

Orviku, K. and U. Sepp. 1972. Stages of Geological Development and Landscape Types of the Islets of the West-Estonian Archipelago. *Geographical Studies* (Tallinn, Estonia), 15-25.

Overpeck, J.T., Rind, D., and R. Goldberg. 1990. Climate-Induced Changes in Forest Disturbance and Vegetation. *Nature*, 343: 51-53.

Paal, J.L., Oja, T.A., and S.F. Kolodyazhnyi. 1989. Taxonomic and Temporal Continuum of Plant Cover. Tallinn, Estonia: Valgus, 182 pp.

Pandivere. 1993. *Pandivere State Water Protection Area*. Jyväskylä, 69 pp.

Pastor, J. and W.M. Post. 1988. Response of Northern Forest to CO₂-Induced Climate Change. *Nature*, 334, 7: 55-58.

Prentice, I.C. 1983. Postglacial Climatic Change: Vegetation Dynamics and the Pollen Record. *Progress in Physical Geography*, 72: 273-286.

Punning, J.M. 1987. Holocene Eustatic Oscillations of the Baltic Sea Level. *Journal of Coastal Research*, 3/4: 505-513.

Punning, J.M. 1993. Sea Level Changes and Paleogeographical History of the Baltic Sea. In: *Sea Level Changes and Their Consequences for Hydrology and Water Management*. Noordwijkerhout, Netherlands, 61-71.

Punning, J.M. (ed.). 1994. *The Influence of Natural and Anthropogenic Factors on the Development of Landscapes*. Tallinn, Estonia: Institute of Ecology, Publ. 2, 227 pp.

Punning, J.M. and A. Raukas. 1985. *Palaeogeography of Northern Europe During Late Pleistocene. Advances of Sciences and Technology*. Moscow, 214 pp. (in Russian).

Punning, J.M., Martma, T., and R. Vaikmäe. 1984. Light Isotope Variations in Carbonate Sediments and Their Palaeogeographical Value. *ZfI Mitteilungen* (Leipzig), 84: 329-336.

Richie, J.T. et al. 1989. Development of a Barley Yield Simulation Model, 4 SDA 86 - CRSR - 2 - 2867. Michigan State University, East Lansing, Michigan.

Rosenzweig, C. and M.L. Parry. 1994. Potential Impact of Climate Change on World Food Supply. *Nature*, 367: 133-138.

Ross, J.K. 1975. *Solar Radiation Regime and Crop Architecture*. Leningrad, USSR: Gidrometizdat, 342 pp. (in Russian).

Sau, A. and R. Viiralt. 1974. The Efficiency and Agronomical Bases of Sprinkler Irrigation of Cultivated Grasslands. *Transactions of the Estonian Agaricultural Academy*, 95: 115-156.

Shugart, H.H. 1984. *A Theory of Forest Dynamics*. New York: Springer-Verlag, 278 pp.

Solomon, A.M. and W.P. Cramer. 1993. Biospheric Implications of Global Environmental Change. In: *Vegetation Dynamics and Global Change*. New York: Chapman & Hall, 25-53.

Solomon, A.M. and R. Leemans. 1990. Climatic Change and Landscape Ecological Response: Issues and Analysis. In: *Landscape-Ecological Impact of Climate Change*. Amsterdam, Netherlands: IOS Press, 293-316.

Statistical Office. 1994. *Statistical Yearbook 1994*. Tallinn, Statistical Office of Estonia, 246 pp.

Svensson, C. and M. Molin. 1994. Fractal Analysis of a Groundwater Level Series from Western Sweden. In: *Nordic Hydrological Conference 1994*. NHP-Report 34, 399-406.

Tappo, E. 1982. *Eesti puistute keskmised takseertunnused puistu enamusiigi, boniteedi ja vanuse järgi*. Tallinn, Estonia: Valgus, 73 pp. (in Estonian).

Tooming, H.G. 1977. Solar Radiation and Formation of Crop Yield. Leningrad, USSR: Gidrometizdat, 200 pp. (in Russian).

Valk, U. and J. Eilart. 1974. *Estonian Forests*. Tallinn, Estonia: Valgus, 307 pp. (in Estonian).

Vallner, L. 1994. Problems of Groundwater Quality Management in Estonia. In: *Groundwater Quality Management: Proceedings of the GQM Conference in Tallinn, September 1993*. IAHS Publications 220, 449-460.

Vallner, L., Sildvee, H., and A. Torim. 1988. Recent Crustal Movements in Estonia. *Jornal of Geodynamics*, 9: 215-223.

Yearbook of Forest. 1994. Economics and Information Centre of Forestry. Tallinn, Estonia, 107 pp.

Figure 1

Figure 2

Figure 3

Figure 4

1 - 100% ; 2 - 90...99% ; 3 - 80...89% ; 4 - 70...79% ; 5 - <70%

Daily average solar radiation

Precipitation

Figure 5

N 0 kg/ha

Precipitation 0%

N 70 kg/ha

Precipitation 0%

N 0 kg/ha

Precipitation -20%

N 70 kg/ha

Precipitation -20%

N 0 kg/ha

Precipitation +20%

N 70 kg/ha

Precipitation +20%

Figure 6

N 0 kg/ha

Precipitation 0%

N 70 kg/ha

Precipitation 0%

N 0 kg/ha

Precipitation -20%

N 70 kg/ha

Precipitation -20%

N 0 kg/ha

Precipitation +20%

N 70 kg/ha

Precipitation +20%

Figure 7

N 0 kg/ha

Precipitation 0%

N 70 kg/ha

Precipitation 0%

N 0 kg/ha

Precipitation -20%

N 70 kg/ha

Precipitation -20%

N 0 kg/ha

Precipitation +20%

N 70 kg/ha

Precipitation +20%

Figure 8

N 0 kg/ha

Precipitation 0%

N 70 kg/ha

Precipitation 0%

N 0 kg/ha

Precipitation -20%

N 70 kg/ha

Precipitation -20%

N 0 kg/ha

Precipitation +20%

N 70 kg/ha

Precipitation +20%

Figure 9

'MONA'

'JULIA'

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18

Figure 19

Figure 20

Figure 21

Figure 22

Figure 23

Figure 24

Figure 25

Figure 26

Figure 27

Figure 28

Figure 29

Figure 30

Figure 31

Figure 32

Figure 33

Figure 35

Figure 35