Impacts of Climate Change on Forest Management and Implications for Swedish Forestry

An analysis based on growth and yield models

Narayanan Subramanian
Faculty of Forest Sciences
Southern Swedish Forest Research Centre
Alnarp

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Cover: An artistic illustration showing the need for planning tools when attempting to fully exploit the advantages and mitigate the risks of future climate change.

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Abstract

While climate change is expected to increase the growth rates of most tree species in Sweden in the future, during this period, there are also increased risks of tree damage due to various risk factors associated with climate change. Therefore, it is necessary to develop adaptive management measures in order to exploit the benefits of climate change and minimize the damage resulting from these risk factors. In this thesis, the interactive effects of future climate change and various risk factors associated with the future climate such as storms, environmental pollutants, pests and pathogens such as root rot and bark beetle on growth and yield of important tree species in Swedish forestry such as Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.) and birch (*Betula spp*) are investigated and possible adaptive management measures are proposed. Simulations of a representative Norway spruce stand in southern Sweden performed using the empirical Heureka-Standwise model (Paper I) showed that forest management practices such as changing the thinning regime, shortening rotation periods, and switching to exotic tree species like hybrid aspen and hybrid larch could effectively reduce damage caused by risk factors and be financially rewarding. Stand-level simulations of six representative stands across Sweden using the ozone parameterized process-based model 3-PG showed that future growth and biomass production could be adversely affected by increasing tropospheric ozone concentrations (Paper II). However, the reduction in growth and biomass production was much lower than the increase due to climate change in all parts of Sweden other than the south. A new landscape-level hybrid model 3PG-Heureka was developed, parameterized and evaluated for Kronoberg county, Sweden (Paper III). The overall performance of the model was satisfactory with highest average error content of 1.5%. The hybrid model's predictions under the future climate scenarios indicated that the storm events could drastically affect the growth and economy of forest landscape in Kronoberg county if the current forest management remains unchanged (Paper IV). Adaptive management regimes featuring shorter rotation periods were predicted to improve annual volume increments and net revenue while reducing storm-felling under two future climate scenarios (RCP4.5 and RCP8.5) but replacing Norway spruce with Scots pine was found to be less effective than reducing the rotation period.

Keywords: climate change, simulation model, landscape modelling, adaptive management, environmental pollutants, storm-felling, root rot, bark beetle

Author's address: Narayanan Subramanian,
Southern Swedish Forest Research Centre,
SLU, Box 49, Rörsjövägen 1, Alnarp,
SE-230 53, Sweden.
E-mail: Narayanan.Subramanian@slu.se
narayanan.subramanian@gmx.com

To Sangeetha and Harshavardhana

Change is the law of the Universe (The essence of Bhagavath Gita)
.....However climate change is an exception.

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Subramanian, N., Bergh, J., Johansson, U., Nilsson, U. & Sallnäs, O. (2016) Adaptation of forest management regimes in southern Sweden to increased risks associated with climate change. *Forests,* 7(1), p. 8.

II Subramanian, N., Karlsson, P.E., Bergh, J. & Nilsson, U. (2015). Impact of Ozone on Sequestration of Carbon by Swedish Forests under Changing Climate: A Modeling Study. *Forest Sciences* 61(3), 445-457.

III Subramanian, N., Nilsson, U., Mossberg, M. & Bergh J. (2016). The 3PG-Heureka hybrid model: Combining process of tree growth based on Light Use Efficiency model, 3-PG and management activities based on Heureka-Regwise Decision Support System. (Manuscript)

IV Subramanian, N., Nilsson, U., Mossberg, M. & Bergh J. (2016). Interactive effects of climate change, weather extremes and adaptive strategies in a nemo-boreal forest landscape: A long-term modeling analysis using the hybrid forest model 3PG-Heureka. (Manuscript)

Papers I-II are reproduced with the permission of the publishers.

The contribution of Narayanan Subramanian (NS) to the papers included in this thesis was as follows:

I NS is the main author. Data analysis and model simulations were done by co-authors. The overall contribution of NS was 60%.

II NS conducted most of the model design, data analysis and model simulations with assistance from co-authors. NS is the main author. The overall contribution of NS was 80%.

III NS conducted most of the model design and model simulations with assistance from co-authors. NS wrote most of the manuscript with assistance from co-authors. The overall contribution of NS was 85%.

IV NS conducted most of the data analysis and model simulations and NS wrote most of the manuscript with assistance from co-authors. The overall contribution of NS was 90%.

Abbreviations

3-PG	Physiological Principles Predicting Growth
a_{mod}	Age modifier
AOT40	Accumulated Ozone exposure above Threshold concentration of 40 parts per billion
APAR	Absorbed Photosynthetically Active Radiation
ASW	Available Soil Water
BAU	Business as usual
BAU+Storm	Business as usual + Storm
CFC	Chlorofluorocarbon
CH_4	Methane
CO_2	Carbon dioxide
CO_{2mod}	CO_2 modifier
CSW	Current Soil Water
dBH	Diameter at breast height
DSS	Decision Support System
EMEP	European Monitoring and Environment Programme
ESRL	Earth System Research Laboratory
EU	European Union
fcc	Fractional Canopy Cover
F_{mod}	Frost modifier
Fr_{mod}	Site fertility modifier
FSC	Forest Stewardship Council
GDP	Gross Domestic Productivity
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf Area Index
LEV	Land Expectation Value
LUE	Light Use Efficiency

N_2O	Nitrous oxide
NFI	National Forest Inventory
NPP	Net Primary Production
O_3	Ozone
OTP	Open Top Chamber
PAS	Promoting alternative tree Species
PEFC	Programme for the Endorsement of Forest Certification
ppb	Parts per billion
PPFD	Photosynthetic Photon Flux Density
ppm	Parts per million
ppm h	Parts per million hours
R	Total monthly incoming solar radiation
RCP	Representative Concentration pathway
SEK	Swedish Kronor
SLA	Specific Leaf Area
SMHI	Swedish Meteorological and Hydrological Institute
SR	Shorter rotation length
SRES	Special Report on Emission Scenarios
SW_{mod}	Soil water modifier
T_{max}	Monthly average of daily maximum temperature
T_{min}	Monthly average of daily minimum temperature
T_{mod}	Temperature modifier
VOC	Volatile Organic Compounds
VPD	Vapour Pressure Deficit
VPD_{mod}	Vapour Pressure Deficit modifier

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1 Introduction

1.1 Background

Sweden is a forest-rich country: around 68% of its total land area is covered by forests, with productive forestland representing around 57% of the total land area (Skogsdata, 2013). Moreover, the forestry sector accounts for approximately 2.2% of the country's Gross Domestic Productivity (GDP) and 11% of its total exports (Skogsstyrelsen, 2014). Because of the country's northerly location (extending from latitudes of 55 °N to 69 °N), the land's productive capacity is low and the landscape is dominated by slow-growing coniferous forest. Forestry is important to Sweden not only because of its contribution to the national economy but also because of its cultural significance to Swedes. Sweden's ancient rights of public access to the countryside have increased the popularity of forests and forestry practices among local population. The most popular outdoor activity among Swedes is walking in the forests (Barklund *et al.*, 2009). Private individuals own around half of the country's forest area, with the other half belonging to private-sector companies, state companies and the state (Skogsstyrelsen, 2014).

The most abundant tree species in Swedish forests are conifers such as Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.), which constitute 80.2% of the total standing volume, while broadleaves such as Downy birch (*Betula pubescens* Ehrh.), Silver birch (*Betula pendula* Roth) constitute another 12.4% (Skogsstyrelsen, 2014). These four tree species together account for almost 92.6% of all trees in Sweden (Skogsstyrelsen, 2014). Other tree species present in appreciable quantities include lodgepole pine (*Pinus contorta* Douglas.) and, aspen (*Populus tremula* L.), alder (*Alnus spp.*) and oak (*Quercus spp.*), as well as smaller numbers of European larch *(Larix decidua* L.), European beech (*Fagus sylvatica* L.), sallow (*Salix spp.*), rowan (*Sorbus acuparia* L.), Norway maple (*Acer platanoides* L.) and European ash (*Fraxinus excelsior* L.).

The Swedish forestry sector is very production-oriented. Even though Sweden has only around 1% of the world's productive forests, it produces 5.5% of the world's sawn timber, 6% of its pulp and 3% of its paper (Skogsindustrierna, 2014; Barklund *et al.*, 2009). Sweden is the third biggest exporter of wood products such as sawn wood, pulp and paper behind only Canada and USA (Skogsindustrierna, 2014). Approximately 73% of the sawn wood, 34% of the pulp and 94% of the paper produced in Sweden were exported during the year 2013, making forest industries a major player in Swedish foreign trade (Skogsstyrelsen, 2014). The forestry sector is thus a key component of the Swedish economy.

Sweden has long tradition of managing forests: almost all of the country's productive forests have been managed to increase timber production for a long period of time (Fries *et al.*, 1997). Consequently, the country has little unmanaged pristine forest. Over 95% of the productive forests in Sweden are primarily used for timber harvesting (Skogsstyrelsen, 2014). These forests are dominated by even-aged conifer monocultures of Norway spruce and Scots pine in Sweden that are managed by clear felling followed by regeneration, either naturally or by planting seedlings. The preferred age of final felling in Swedish boreal forests is 70-100 years. Clear felling accounts for 96% of the total annual final felling in Sweden, with the remainder being harvested by other means such as selection felling (Thuresson, 2001). The standing timber volume in Swedish forests is increasing because the average harvesting rate over the last two decades is only around 74% of the total annual volume growth rate during the same period (Skogsdata, 2013). In addition to production, biodiversity conservation has a key role in Swedish forestry sector. The Swedish forest act gives equal importance to production and environmental goals for managed forests (Lundmark *et al.*, 2014). National parks, nature reserves and habitat protection areas comprise around 7% of the total forest area in Sweden (Skogsstyrelsen, 2014). These protected areas even cover some traditional production forests; around 3.6% of productive forests are formally protected (Skogsstyrelsen, 2014). All forest owners are obliged to conserve biodiversity, protect recreational values, water catchment areas and soil in addition to sustain wood production (Lundmark *et al.*, 2014). Approximately 83% of the productive forest area in Sweden is certified either by the Forest Stewardship Council (FSC) or the Programme for the Endorsement of Forest Certification (PEFC), thus ensuring that environmental and social considerations are prioritized highly in Swedish forestry and protected to a greater degree than is required by law (Keskitalo & Liljenfeldt, 2014).

National Forest Inventories (NFI) have been conducted regularly in Swedish forests since the 1920s (SLU, 2015). As a result, Sweden has extensive long-term forest data describing the status of its forest resources on regional and national scales. This makes it possible to rigorously analyse the consequences of different management regimes that have been applied over the course of history, meaning that the Swedish forestry sector is well positioned to identify and adopt optimal management strategies to ensure sustainable forest management in the future.

1.2 Impacts of climate change on boreal forests

Climate change is identified by considering climate variables such as the atmospheric CO_2 concentration, temperature, precipitation, and wind strength, and studying trends in their average variability and extreme values. If a particular climate variable or group of variables takes values outside its historical variability range for an extended period of time, climate change is said to have occurred. Atmospheric greenhouse gas (GHG) concentrations increased markedly over the last century, mainly because of emissions from fossil fuel combustion, land use changes and industrial emissions. This in turn raised the mean air surface temperature, and this trend is expected to continue during the 21st century (Solomon *et al.*, 2007; Keeling & Whorf, 2005). The most abundant GHGs in the atmosphere are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and chlorofluorocarbons (CFCs); the atmospheric concentrations of all these gases have increased since the 1750s, mainly because of human activity (IPCC, 2013). In the 1800s the atmospheric CO_2 concentration was about 280 parts per million (ppm), today it is around 400 ppm, and it is predicted to increase to 538-936 ppm by the end of this century (IPCC, 2013; Houghton *et al.*, 2001).

Stratospheric ozone accounts for 10% of the total radiative forcing due to GHGs, behind only CO_2 (which accounts for 56%) and CH_4 (11%), and tropospheric ozone is the GHG that is most damaging to vegetation (Forster *et al.*, 2007; Matyssek *et al.*, 2007; Paoletti *et al.*, 2007). Tropospheric ozone is directly emitted as a result of industrial activities and is also formed as a secondary pollutant via a chemical reaction involving volatile organic compounds (VOC) such as CH_4 in the presence of sunlight (Karnosky *et al.*, 2005). At the end of the 19th century, the tropospheric ozone concentration in central Europe was around 10 parts per million hours (ppm h) Accumulated

Ozone exposure above Threshold concentration of 40 ppb[1] (AOT40; Karlsson *et al.*, 2009; Karlsson *et al.*, 2004b; Wallin *et al.*, 2002), which was much higher than the concentration in the pre-industrial 1700s (Volz & Kley, 1988). Industrial emissions have caused tropospheric ozone concentrations to increase over the last century, to a level that is harmful to vegetation (Karnosky *et al.*, 2007; Matyssek *et al.*, 2007; Skärby *et al.*, 1998). The current tropospheric ozone concentration is above 40 ppm h AOT40 in many parts of the northern hemisphere, and around 24-28 ppm h AOT40 in central Europe (Karlsson, 2012). The current mean tropospheric ozone concentration in Sweden as a whole is around 5 ppm h AOT40, but the mean annual tropospheric ozone concentration has reached around 11-26 ppm h AOT40 in southern Sweden, demonstrating that there is a clear gradient in tropospheric ozone concentration from south to north (Karlsson *et al.*, 2009). It is very likely that tropospheric ozone concentrations will continue to rise in the future because emissions of precursor pollutants such as VOCs are expected to increase with population growth (Ainsworth *et al.*, 2012). Rising tropospheric ozone concentrations could pose a serious problem for vegetation in the future, which could be aggravated by climate change (Klingberg *et al.*, 2014).

The increases in temperature due to global warming are most pronounced at higher latitudes. In Europe the mean temperature is predicted to increase by 2.5-5 ^{o}C in summer and 3.5-7.5 ^{o}C in winter by the end of this century (Jacob *et al.*, 2014; Cattiaux *et al.*, 2013). Therefore the boreal coniferous forests of northern Europe are predicted to be strongly affected by future climate change (Bergh *et al.*, 2003; Houghton *et al.*, 2001). In keeping with this prediction, the highest increases in average winter temperatures observed to date have occurred in the boreal zone (Rummukainen, 2012). The average annual number of frost days is predicted to decline across Europe. These factors tend to promote tree growth. However, climate change also induces trees to flush earlier than they would otherwise, increasing their risk of exposure to early frost events (Langvall, 2011). Moreover, some studies have suggested that climate change could increase the intensity and duration of extreme cold periods thus increasing the incidence of frost events in the future (Rummukainen, 2012). It is not clear how climate change will affect average and extreme wind speeds in future, and there is considerable uncertainty associated with the prediction of stochastic events like storms (Rummukainen, 2012). According to Pryor et al (2012), the wind energy density for the Baltic sea region (including southern Sweden) can be expected to increase by around

1. AOT40 is the sum of difference between hourly mean ozone concentration in parts per billion (ppb) and 40 ppb for each hour when concentration exceeds 40 ppb (Karlsson *et al.*, 2004a; Skärby *et al.*, 1995).

10-15% relative to current levels in the near future. Climate change is predicted to increase the incidence of high intensity storms over Western Europe during early autumn (Haarsma *et al.*, 2013).

The boreal forests of Sweden, which are important sources of timber and paper feedstocks as well as being important recreational sites, have recently been affected by climate change (Bergh *et al.*, 2010) and by air pollution including elevated tropospheric ozone levels (Karlsson *et al.*, 2009). Climate change affects the physiological processes of forests and thus alters their phenology, photosynthetic capacity and respiration as well as the availability of soil nutrients (Richardson *et al.*, 2013; Stocker *et al.*, 2013; Hänninen & Tanino, 2011; Ågren *et al.*, 2008; Bergh *et al.*, 1998). Tropospheric ozone affects vegetation growth by causing cellular damage after entering the leaves via stomatal gas exchange.

There is a growing body of evidence showing that species interactions and competitive responses under changing climatic conditions are highly complex and frequently rather unpredictable (Suttle *et al.*, 2007). Therefore impact studies should explore the broad-spectrum variation and uncertainty of climate change when considering its effects on the biological responses of systems such as forests rather than simply examining the effects of mean projected trends (Lindner *et al.*, 2014).

There is substantial uncertainty regarding future climatic conditions. To manage this uncertainty, it is necessary to use flexible strategic approaches that make it possible to change one's course of action as conditions change (Hobbs *et al.*, 2006). Suitable strategic approaches for coping with climate change include adaptation strategies and mitigation strategies. Adaptation strategies help forested ecosystems to accommodate changes while mitigation strategies include actions that reduce causes of stress, in this case the anthropogenic influence on the global climate (Millar *et al.*, 2007).

1.3 Management options in adaptation strategies

Adaptive management involves learning by experience and iteratively incorporating lessons into future plans so as to help forested ecosystems to accommodate changes resulting from climate change (Millar *et al.*, 2007). When using an adaptation strategy, managers must be flexible when making decisions, willing to take risks, provide constant feedback, and be willing to change their course of action as the conditions change (Hobbs *et al.*, 2006). There are a wide range of ways in which future climate change could potentially affect forests, which can only be partially predicted in terms of their effects on (i) growth and productivity, (ii) species suitability and (iii) the disturbance responses of different tree species (Lindner *et al.*, 2014). Adaptation strategies can be implemented in two different ways, depending on the extent to which climate change is expected to affect these three factors.

"Promoting resilience" to change is the most commonly suggested adaptive strategy for managing the effects of climate change in forestry (Spittlehouse & Stewart, 2004; Price & Neville, 2003). Resilient forests can not only accommodate gradual changes related to climate change but also tend to return toward their prior condition after disturbance, either naturally or with the assistance of management interventions (Millar *et al.*, 2007). Management options such as surplus seed sowing and intensive management during the early years of establishment can enable the retention of desired species even if the site has stopped being optimal for them and will thereby enhance the forest's resilience in the face of climate change (Spittlehouse & Stewart, 2004). Resilience of a desired forest state is also promoted by maintaining a heterogeneous stand structure, prescribed fire treatment and sanitation harvesting (Drever *et al.*, 2006). Maintaining and improving resilience requires intensive physical work and high costs because changes facilitated by climate accumulate over time (Millar *et al.*, 2007).

"Enabling" forests to respond to change facilitated by climate involves intentionally mimicking and enabling on-going natural adaptive processes such as species dispersal and migration, population mortality, colonization and changes in species dominances and community composition (Millar *et al.*, 2007). The ultimate goal is to encourage gradual adaptation and transition processes, thereby avoiding rapid catastrophic conversions. Management options in this adaptive strategy include modifying harvest schedules, altering thinning prescriptions, regenerating with different tree species, shifting desired tree species to new locations, and assisted migration to promote on-going natural adaptive process (Millar *et al.*, 2007; Briceño-Elizondo *et al.*, 2006). It is necessary to understand the ecological behaviour of the relevant tree species with a high level of confidence before deciding to encourage their gradual adaptation. Changing the management pattern of a tree species or introducing tree species to new areas that are expected to become suitable habitats in the future requires substantial knowledge of the tree species and can only practically be implemented for a few tree species that are of particular interest or concern.

1.4 Management options in mitigation strategies

Mitigation strategies involve management actions that reduce anthropogenic emissions of GHGs and carbon. The forestry sector can contribute to mitigation efforts in many ways. The goal of a mitigation strategy is to use forest ecosystems to: (i) reduce GHG emissions and (ii) promote growth and carbon sequestration, thereby reducing the anthropogenic contribution to climate change.

Forests are a major source of GHG, which are released during wildfires and as a result of high mortality events such as extensive storm damage, pest attacks, or outbreaks of disease. Wildfires in boreal forests account for 9% of global carbon emissions from fires (van der Werf *et al.*, 2010), and the severity and intensity of wildfires in boreal forests are predicted to increase in future (de Groot *et al.*, 2013). Although wildfires occur relatively frequently in the boreal forests of Canada and Russia, they have become much rare in Sweden. The decline in Swedish wildfires has been attributed to changes in forest structure and species composition as well as active fire suppression measures that have been undertaken (Wallenius, 2011; Zackrisson, 1977). Global warming will probably increase the impact of pests and pathogens on forest ecosystems. Root rot fungi (*Heterobasidion annosum* (Fr.) Bref.) have caused high mortality and subsequent reduction in growth in Scots pine and Norway spruce stands in Sweden (Wang *et al.*, 2014; Oliva *et al.*, 2010). Storm damage and bark beetle (*Ips typographus* L.) infestations are the most devastating disturbances in Scandinavian forest ecosystems (Stadelmann *et al.*, 2014); they account for 53% and 8%, respectively, of all forest damage in Europe and are responsible for large amounts of sanitation felling. Moreover, the frequency and intensity of these natural disturbance has increased in recent years (Schelhaas *et al.*, 2003). In January 2005 southern Sweden was hit by a major storm "Gudrun", which caused massive damage corresponding to 110% of the country's average annual harvest rate, resulting in a drastic increase in deforested areas (Seidl & Blennow, 2012). While these natural disturbances are unintentional source of carbon emissions, they could lead to the loss of huge amounts of sequestered carbon.

Mitigation measures to minimize the carbon emissions in these circumstances are to increase forests' resistance to fire, storm, pests and diseases. Management options suitable for this purpose include establishing fire-lines around high-risk areas, increasing trees' storm resistance via high intensity first thinnings and promoting biological control of pests.

Promoting tree growth provides an efficient and inexpensive means of removing CO_2 from the atmosphere and producing raw materials to replace fossil fuels. Forests in themselves are also large carbon stores, and increasing standing volumes means greater sequestration of atmospheric CO_2. Similarly, forest products with long life spans help to mitigate climate change by storing carbon for an extended period of time (Canadell & Raupach, 2008). An important difference is that the displacement of fossil fuels results in a permanent benefit whereas the carbon storage option is temporary, i.e. the benefit lasts only until the stored carbon is released back into the atmosphere.

Many forest management practices can increase growth, promote carbon sequestration and the usage of forest bioenergy in Sweden (Nilsson *et al.*, 2011; Larsson *et al.*, 2009). Examples include changing the thinning regime or rotation age, introducing exotic tree species, taking measures to safeguard biodiversity, using improved genetic material, utilization of harvest residues, propagating short rotation bio-energy crops and increased fertilization thus increasing carbon sequestered by forests and increasing utilization of forest resources as bioenergy (Rytter *et al.*, 2015; Nilsson *et al.*, 2011).

Sustainably managed forests could be reliable source of forest products such as sawn wood, paper and pulp and as an added advantage they continue to sequester carbon as they grow, thus significantly reducing atmospheric CO_2 levels. A combination of sensible forest management, utilization of logging residues for bioenergy production, and manufacturing of wood-based products could help to reduce the atmospheric CO_2 concentrations. Bioenergy generated from wood biomass harvested from sustainably managed forests is considered carbon neutral because all carbon released during its utilization was previously sequestered during forest re-growth (Nabuurs *et al.*, 2007).

High concentrations of secondary pollutants such as tropospheric ozone can significantly reduce tree growth and thus affect forests' carbon sequestration capacity. The annual biomass production in birch and Norway spruce were reduced by 21.5% and 20% respectively, when the trees were exposed to high ozone concentration of 60 ppm h and 20 ppm h AOT40 (Karlsson *et al.*, 2003; Skärby *et al.*, 1995). Economic losses due to reduced tree growth and timber yield caused by the increased tropospheric ozone concentration (relative to that in the pre-industrial period) in Sweden are estimated to be around 500 million SEK yr^{-1} (Karlsson *et al.*, 2005). Industrial emissions are the biggest source of secondary pollutants such as ozone. One way to reduce tropospheric ozone concentrations would be to reduce the emissions of precursor pollutants such as VOC.

The main challenge in a mitigation strategy is to determine how different forest management regimes and wood use strategies can best contribute to mitigation (Lundmark *et al.*, 2014). Recent studies have shown that Swedish forests have the capacity to mitigate 60 million tons of CO_2 equivalents annually on a long-term basis with current forestry practices, which is almost equal to the country's total annual GHG emissions (Lundmark *et al.*, 2014). Mitigation strategies can thus clearly contribute significantly to the climatic benefits provided by Sweden's forestry sector.

1.5 Integrated management strategy

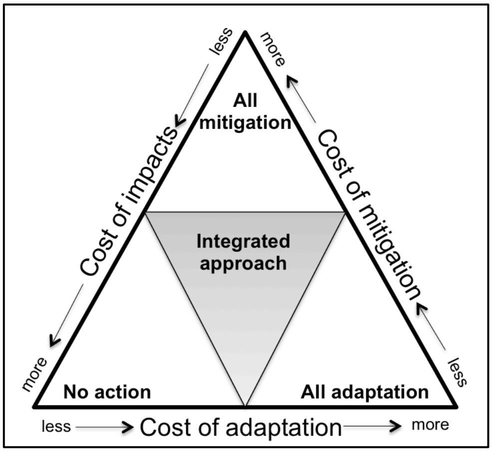

Figure 1. Schematic depiction of an integrated approach to sustainable forest management (Klein *et al.*, 2007).

Given the high levels of uncertainty about future climatic outcomes, no single approach to forest management will be suitable for all conceivable situations (Hobbs *et al.*, 2006; Spittlehouse & Stewart, 2004). An integrated approach in which various treatments and practices are combined and tailored to suit the actual situation should thus be adopted (Figure 1). Strategic decisions will depend on the spatial and temporal scale of decision-making and the costs involved. Mitigation strategies have global benefits, whereas adaptation strategy works best for a regional scale (Klein *et al.*, 2005). Forest management planning at regional and national scales involve different levels and types of uncertainty than management planning at the stand or estate scale. In an integrated approach, each management option must be assessed to determine its risk of jeopardizing forests' capacity to deliver other ecosystem services such as biodiversity, water quality, and social and cultural services (McDermott *et al.*, 2010; Sukhdev *et al.*, 2010). The ideal integrated management option would be the one that supports carbon sequestration in the forest ecosystem while simultaneously enhancing other ecosystem services. Therefore, a forest manager practicing an integrated approach should have a thorough understanding of the expected future growth, productivity, and suitability of the desired tree species and its ecosystem, as well as the disturbances that are likely to occur. Simulations and models are needed to accurately predict many of these factors.

1.6 Simulation models used in forestry

A simulation model is an abstraction of the natural dynamics of tree growth, mortality, and disturbances into logical mathematical functions that can be implemented in a computer programme. The development and use of simulation models in forestry began in the 1980s after the introduction of personal computers and pioneering models such as ORGANON, Forest-BGC and 3-PG (Weiskittel *et al.*, 2011). Forest management planning and policymaking require careful analysis of the available data and a thorough understanding of possible future trends in the growth, productivity, suitability and disturbances of the forest ecosystem. Simple and efficient simulation models for simulating forest growth and yield are therefore core tools for management planning. The most important tasks of a simulation model are to predict future yields and the likely effects of different silvicultural management regimes at the tree-, stand-, landscape- or national-level.

It is very difficult to understand the behaviour of a forest ecosystem simply by analysing field or laboratory measurements. Long-term silvicultural experiments especially in boreal forests, are generally time consuming and costly, and it can be difficult to obtain meaningful information on many aspects of a forest ecosystem during the course of a single human lifetime. Therefore, forest managers must often rely on simulations to obtain any kind of information on growth and yields to support planning and management. If growth and yield statistics are available for stands at a particular site, simulation models can be used to calculate the future growth and yield of those stands under different hypothetical silvicultural management regimes or climatic conditions, which would not be possible otherwise. There are three kinds of simulation models that are widely used in forestry: (i) Empirical models (ii) Process-based models and (iii) Hybrid models, each of which has its own advantages and limitations (Weiskittel *et al.*, 2011; Landsberg & Sands, 2010; Peng *et al.*, 2002; Mäkelä *et al.*, 2000; Landsberg & Coops, 1999; Korzukhin *et al.*, 1996).

1.6.1 Empirical models

Empirical models are entirely based on measurements and observations collected in the field. These data are needed to develop the model's logic (which is based on regression curves), and separate datasets are then needed to calibrate and validate the resulting model. Empirical models in forestry are primarily used to predict stand development and yield over time (Weiskittel *et al.*, 2011). They are used extensively in the Swedish forestry sector. Empirically-based stand-level growth functions (Elfving & Nyström, 2010; Ekö, 1985) and individual tree growth functions (Elfving & Nyström, 2010;

Söderberg, 1986) developed using Swedish NFI data could be applied to all major tree species in Sweden (Fahlvik *et al.*, 2014). In addition, the empirically based Heureka Decision Support System (DSS) is widely used by Swedish forest companies and other research institutes for long-term forestry planning (Wikström *et al.*, 2011; Elfving & Nyström, 2010).

1.6.2 Process-based models

Process-based models simulate growth based on eco-physiological processes such as photosynthesis, respiration and decomposition, as well as the soil-water balance and nutrient cycling, all of which are treated as primary effects of environmental factors such as the light, temperature, atmospheric CO_2 concentration and soil water content (Peng *et al.*, 2002; Mäkelä *et al.*, 2000). The main advantage of process-based models is that the inclusion of these eco-physiological processes allows users to generate and test alternative hypotheses and makes it possible to describe how these processes interact over a long-term forecast period under changing environmental conditions (Peng *et al.*, 2002). Process-based carbon balance models compute the assimilation of carbon and its allocation to different organization levels in the stand such as the foliage, stem and roots (Mäkelä *et al.*, 2000). In addition, process-based forest growth models such as 3-PG (Landsberg & Sands, 2010; Landsberg & Waring, 1997) and BIOMASS (McMurtrie & Wolf, 1983a; McMurtrie & Wolf, 1983b) are used in Sweden to predict the state of the forest under changing climate at the stand-level (Subramanian *et al.*, 2015; Getahun, 2013; Subramanian, 2010; Bergh *et al.*, 2005; Bergh *et al.*, 1998).

1.6.3 Limitations of empirical and process-based models

Although empirical models and process-based models are widely used in the Swedish forestry sector, they both have limitations. As a result of increased nitrogen deposition, better management activities and increased atmospheric CO_2 concentrations, the annual growth rate in Swedish forests has increased from 80 million m^3 during the 1970s (Elfving & Tegnhammar, 1996) to around 125 million m^3 during 2014 (Skogsstyrelsen, 2014). This trend will continue unless very drastic changes occur in the near future, which will make the long-term growth and yield forecasts of empirical models increasingly unreliable. For example, all of the growth simulators used in the Heureka model underestimated the basal area growth for mature trees with large initial basal areas (Fahlvik *et al.*, 2014). These growth simulators are based on even-aged monocultures that are traditionally managed and they can be used to forecast the growth and yield of forest stands in the near future, during which the impact of climate change on forest stand is expected to be minimal. However, the reliability of their growth predictions over longer periods of time is highly uncertain.

Even though process-based models are widely used as research tools in forestry, they are rarely used to guide practical decision-making. Many process-based forest models such as FOREST-BGC, CENTURY, TREEGROW cannot predict stand characteristics such as basal area, dBH and mortality, which limits their practical utility (Peng *et al.*, 2002; Metherall *et al.*, 1993; Running & Coughlan, 1988). While process-based models such as 3-PG can predict stand variables such as basal area, diameter and mortality, they are unpopular among forest managers because they require a large number of input variables and parameters (Peng *et al.*, 2002), many of which are not readily available. In addition, the carbon allocation equations, mortality equations, management functions and regeneration equations implemented in process-based models are associated with high levels of uncertainty (Landsberg & Sands, 2010; Mäkelä *et al.*, 2000; Weller, 1987; Zeide, 1987).

The discussion above clearly demonstrates that both empirical and process-based models present considerable uncertainty when used for long-term forest planning. There is thus a growing demand for alternative models that can be applied to diverse forest structures in a given operational level and can predict the potential effects of future changes in the global environment such as climate change, land use change, and changes in forest harvesting patterns (Von Teuffel *et al.*, 2006). In general, the weaknesses of process-based models are strengths of empirical models and vice versa (Peng *et al.*, 2002). An integrated modelling approach combining both empirical and process-based models could thus enable better prediction of forest growth under a changing climate and thereby provide more reliable estimates for long-term forest planning.

1.6.4 Hybrid models

Hybrid models are a recently developed class of forest models that aim to combine the strengths of process-based and empirical models and thereby compensate for their individual weaknesses (Kimmins *et al.*, 1999). Hybrid models have several advantages that make them attractive to forest managers (Taylor *et al.*, 2009): (i) they use eco-physiological principles to predict growth and empirical allometries to predict the effects of other factors such as management activities, (ii) they offer increased flexibility because the models can be applied over wider spatial and temporal scales than alternative model types, (iii) they require comparatively little input data, and (iv) they offer simplified empirical representations of silvicultural treatments such as thinning, final felling and fertilization (Weiskittel *et al.*, 2011; Johnsen *et al.*, 2001). Therefore, hybrid models can be regarded as the future of forest growth modelling. However, they are not yet widely used in the Swedish forestry sector, and hybrid models such as 3PG-Heureka are currently in an early stage of development. The main challenge to be overcome when developing and refining hybrid models is their internal complexity.

2 Objectives

The overall objective of this thesis is to investigate the impact of future climate change on the growth and yield of important tree species in Swedish forestry sector such as Norway spruce, Scots pine and birch and to determine how future silvicultural management activities could be planned in order to ensure that Swedish society and Sweden's forest-based industries derive the greatest possible benefit from the country's forests.

- The objective of paper I was to investigate how the productivity, economic performance, and risk exposure of Norway spruce stands in southern Sweden will be affected in future by (i) storm events, bark beetle attacks and root rot, (ii) changing the existing thinning programme and shortening the existing rotation periods, and (iii) replacing Norway spruce with alternative tree species.
- The objective of paper II was to modify the process-based 3-PG model to account for the effects of tropospheric ozone on various physiological processes in Norway spruce, Scots pine, and birch. The modifications were based on experimental Open Top Chamber (OTP) measurements. Because the model was already capable of accounting for the effects of changes in atmospheric CO_2 levels and increasing temperature, this modification made it possible to explore the combined effects of climate change and tropospheric ozone levels on the Net Primary Production (NPP) and carbon sequestration potential of Swedish forests in current and future climate scenarios.
- Paper III presents a hybrid model 3PG-Heureka combining the growth simulators of the process-based 3-PG model and the management functions of the empirically based Decision Support System (DSS) Heureka-Regwise. Its objectives are to (i) present the major assumptions and mathematical functions of the 3PG-Heureka hybrid model, (ii) parameterize the model

using NFI data and calibrate the model using baseline Heureka-Regwise simulations, and (iii) discuss the model's potential applications and future development.

- The main objectives of paper IV were to (i) investigate the interactive effects of climate change and extreme weather events on the productivity and economic performance of forests in Kronoberg county, southern Sweden, and (ii) to determine the potential of alternative management programmes to reduce damage caused by extreme weather events as part of an adaptive strategy. Alternative management programmes considered include a modified thinning programme, reducing rotation periods, and promoting the plantation of alternative tree species.

3 Materials and methods

3.1 Study area

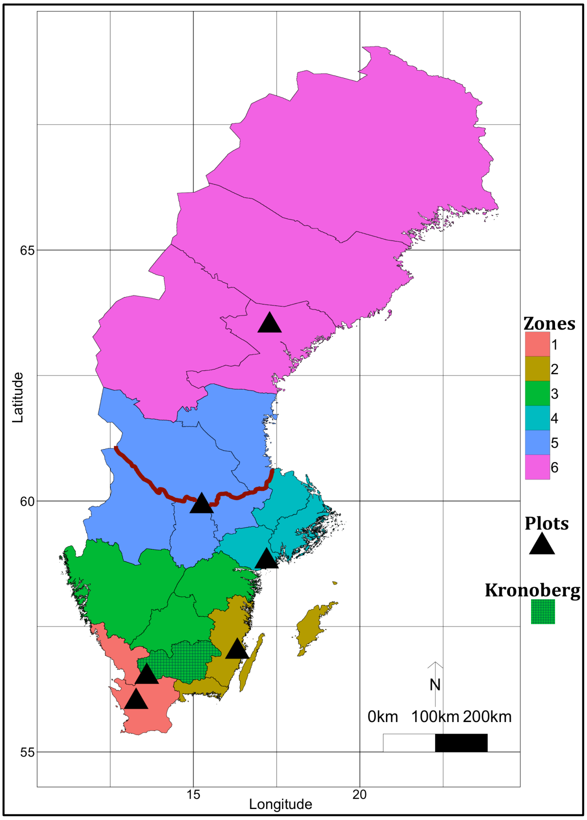

Figure 2. Map showing Kronoberg county (Paper III and IV), a division of Sweden in to different zones based on the tropospheric ozone concentration, and the location of the representative study plots in each zone (Paper II). The map also shows the boundary between northern and southern Sweden (Paper I and II).

The initial data for the simulations were obtained from one representative hypothetical Norway spruce stand in southern Sweden in the case of Paper I (Figure 2) and from six representative hypothetical mature forest stands located in different zones within Sweden having different tropospheric ozone concentrations (Paper II). All of these stands were between 20 and 42 years old, and even-aged, with site index (dominant height at a total age of 100 years; Elfving & Kiviste, 1997) values ranging from 22-34 m (spruce), 22-28 m (pine) and 20-22 m (birch). The soil moisture class of the stands was either mesic or moist.

Papers III and IV describe landscape-level analyses of Kronoberg county, southern Sweden. The total productive forest area in this county is around 0.65 million ha, the average standing volume is around 142 m^3 ha^{-1} (Skogsstyrelsen, 2014), and the mean site index is approximately 27 m (Fridman *et al.*, 2014). The landscape is dominated by conifer stands and the major tree species is Norway spruce. The total annual precipitation in the area is approximately 750 mm and the monthly mean temperature is around 16.5 °C during summer, and -0.7 °C during winter (SMHI, 2016).

3.2 The Heureka-Decision Support System (DSS)

Heureka model is an empirically based DSS developed by the Swedish University of Agricultural Sciences. It forecasts growth and yield of forest stands from an early stage (about 5 years after planting) to final felling based on predictive five-year changes in the height and diameter of individual trees in circular plots a radius of 10 m (Fahlvik *et al.*, 2014; Wikström *et al.*, 2011). The Heureka DSS comprises three different applications:

3.2.1 Heureka-Standwise

Heureka-Standwise is used for stand-level analysis. It is based on a model that simulates one stand at a time with a minimum time resolution of five years. Management activities such as cleaning, pre-commercial thinning (PCT), thinning, final felling and regeneration can be implemented in each time step if necessary. It also has innovative options for two- and three-dimensional visualization of the data for the simulated stand (SLU, 2014).

3.2.2 Heureka-Planwise

Heureka-Planwise is used for estate level analysis. It is based on a model that simulates several stands at a time, with a minimum time-resolution of five years. An optimization model generates alternative management scenarios for each stand, and an optimized estate-level management regime is devised on the basis of a user-supplied objective (SLU, 2014).

3.2.3 Heureka-Regwise

Heureka-Regwise is used for regional or national-level analysis based on long-term simulations of large landscapes. NFI data are normally used as the input data for this model. Management activities such as cleaning, PCT, thinning, final felling and regeneration are implemented by empirically-based functions (SLU, 2014).

Although the Heureka DSS is based on three separate modelling applications for simulations on different spatial scales, all of the applications use the same mortality model and the same empirical functions for quantities such as the basal area and height increments for individual trees, and the stand basal area increment.

3.2.4 Basic concept of Heureka model

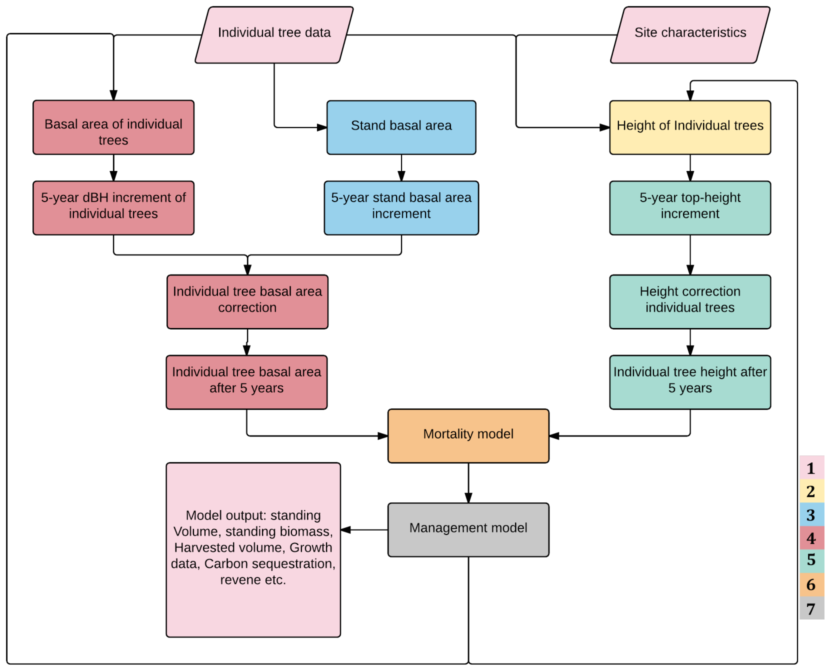

Figure 3. Schematic representation of the Heureka model. The colours show the different model components such as (1) the input-output module, (2) the estimation of individual tree heights at the start of the simulation, (3) the stand basal area increment function, (4) the five-year dBH increment functions for individual trees, (5) the height increment function for individual trees, (6) the mortality model and (7) the management model.

Heureka-DSS has five different sub-models and a database connector that connects the applications to an input database and results database (Figure 3). The sub-models of the Heureka-DSS are:

1. The input-output module
2. The estimation of individual tree height at the start of the simulation
3. The stand basal area increment function
4. The basal area increment functions for individual trees
5. The height increment function for individual trees
6. The mortality model
7. The management model

Detailed descriptions of the sub-models and growth functions used in the Heureka-DSS could be found in the publications of Elfving and Nyström (2010) and Fahlvik *et al.* (2014). The initial heights of individual trees are estimated with a function developed by Söderberg (1992) and the five-year basal area growth is estimated using a stand-level growth function for all trees in Sweden (Elfving & Nyström, 2010). In parallel, the five-year dBH increment of individual trees is estimated using individual tree growth functions. The individual tree diameters are then normalized to ensure that they sum to the basal area computed using stand-level functions (Elfving & Nyström, 2010). The five year potential height increment of individual trees is estimated using the height growth functions for top-height trees (Elfving & Nyström, 2010). The height growth is then corrected using a modifier that depends on the basal area of larger trees in the plot. The volumes of individual trees are calculated from their estimated dBH values and height (Brandel, 1990).

Tree mortality is modeled using a two-step approach (Figure 3). In the first step, the average mortality for each stand is estimated and in the second it is distributed over the individual trees (Fridman & Ståhl, 2001). Average mortality is modeled with a logistic function whose independent variables include the basal area of larger trees, soil moisture, vegetation type and thinning history. The probability of mortality of individual trees is modeled with tree-species-specific logistic functions developed by Fridman and Ståhl (2001). The independent variables of these functions include the basal area, individual tree diameter, thinning history and mean diameter.

The management or treatment model is a main component of the Heureka-DSS (Wikström *et al.*, 2011; Elfving & Nyström, 2010). Three different management systems can be modelled with this DSS: even-aged, uneven-aged, and no management (Figure 3). The model can also simulate forest growth in combination with hypothetical storm damage. Treatment programmes that can be simulated include planting, natural regeneration, sowing, cleaning, PCT, thinning, selection felling, removal of seed trees, tree retention, and fertilization. In addition, it is possible to set selected stands aside for nature conservation (Wikström *et al.*, 2011). Multiple management systems can be simulated by dividing forest stands into user-created groups called forest domains.

Thinning programmes can be specified to prioritize desired tree species (deciduous or conifers, Norway spruce or Scots pine), thinning styles (from above or below, etc.), and desired intensities. Several thinning guides are available including polynomial, Skogsstyrelsen (1984), stem density, and logarithmic. Thinning guides are empirical functions that take input data such as the stand's top-height and site index. Several final felling options such as seed tree retention, clear felling, and shelterwood retention are also available, and there is an option to model the extraction of bio-energy during final felling. The regeneration function allows the user to choose whether regeneration will occur with Scots pine, Norway spruce, Birch and Lodgepole pine, at planting intensities of 0-100%. Soil scarification can also be specified if necessary during regeneration, and the intensity of soil scarification can be tailored to suit the site's soil moisture class (dry, mesic, or moist). If necessary the regeneration and soil preparation activities could be delayed, leaving the site fallow to facilitate recovery from the impact of final felling.

3.2.5 Data input

The model's input data are individual tree data such as dBH (mm), tree age (years), basal area (m^2 ha^{-1}), the dBH of the largest tree in the plot and site characteristics such as latitude (^oN), altitude (m), proportion of pine and spruce in the plot, and distance from coastline (km).

3.2.6 Data output

The model produces a wide range of output variables including standing biomass, standing volume, carbon sequestration, growth data, harvested volumes, revenue obtained and volumes of harvested pulpwood and timber.

3.3 The 3-PG model

The process-based model 3-PG (Physiological Principles Predicting Growth) was developed by Landsberg and Waring (1997). It is a simple stand-level model that requires only a few parameter values as well as a limited amount of climate and initial stand data as inputs for simulation.

3.3.1 Basic concept of the 3-PG model

The 3-PG model consists of five different sub-models:

1. Soil water balance sub-model
2. Biomass production sub-model
3. Biomass allocation sub-model
4. Mortality sub-model
5. Management sub-model

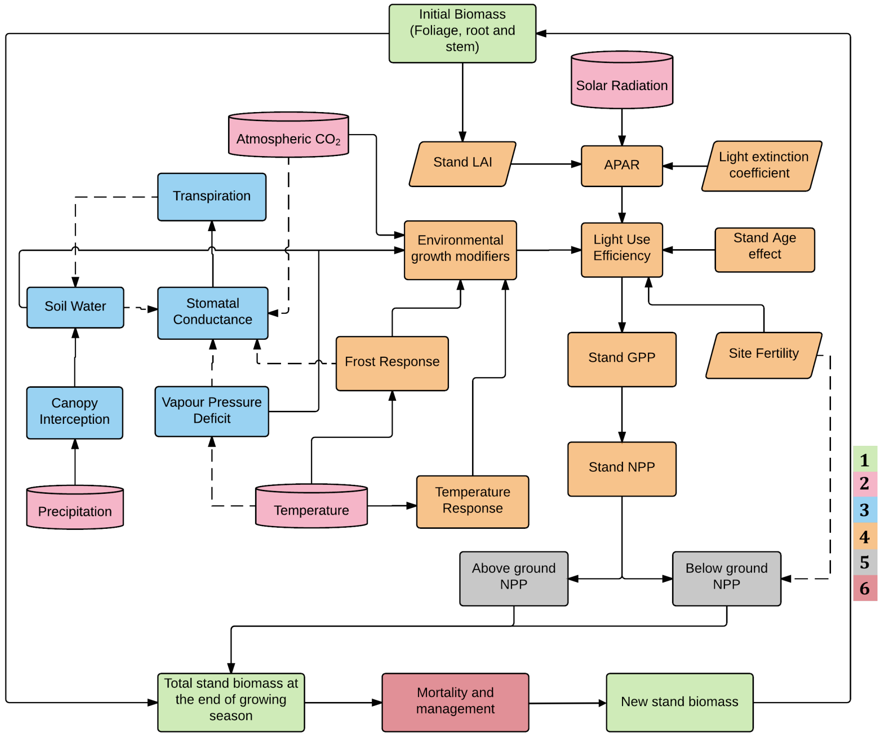

Figure 4. Schematic representation of the 3-PG model. The colours show the different sub-models and other model components: (1) Initial stand data, (2) Climate data, (3) Soil water balance sub-model, (4) Biomass production sub-model, (5) Biomass allocation sub-model, (6) Mortality and management sub-model. Solid lines represent direct relationships and dotted lines represent indirect relationships.

In the 3-PG model, the Absorbed Photosynthetically Active Radiation (APAR) value for the stand foliage is calculated using Beer's law (Figure 4), from the total incoming solar radiation, Leaf area Index (LAI), the extinction coefficient of light, and the fractional canopy cover (fcc) of the forest stand (Landsberg & Sands, 2010; Sands, 2004). It is assumed that fcc is constant over a rotation period. The stand LAI is calculated from the biomass of the foliage and the Specific Leaf Area (SLA). The SLA is assumed to be constant over the entire simulated period (Landsberg & Sands, 2010).

The Light Use Efficiency (LUE) of the forest stand is a function of APAR and the environmental limitations on tree growth imposed by the Vapour Pressure Deficit (VPD), soil water content, site fertility, stand age, atmospheric CO_2 concentration, temperature response, frost response, and the stand's canopy quantum efficiency (Landsberg & Sands, 2010). These environmental constraints were implemented as growth modifiers in the LUE function (Figure 4). Detailed descriptions of the procedures used to compute the different dimensionless environmental growth modifiers have been published (Landsberg & Sands, 2010; Almeida *et al.*, 2009; Landsberg *et al.*, 2005; Sands & Landsberg, 2002; Landsberg & Waring, 1997).

The LUE is calculated using the lower of the VPD-modifier and the soil water-modifier (Landsberg & Sands, 2010). This is because at high VPD values (corresponding to a low VPD-modifier), the stomata close to limit the transpiration rate, so the soil water modifier is not a limiting factor (Landsberg & Waring, 1997). Similarly, when the soil water deficit is high (corresponding to a lower soil water modifier), the canopy conductance is highly influenced by the soil water content, and the soil water content will be the limiting factor rather than the canopy conductance (Landsberg & Waring, 1997). The monthly Gross Primary Production (GPP tons ha^{-1}) was calculated from the APAR, LUE and number of days in the month (Landsberg & Sands, 2010). The biomass accumulated in a forest stand per month, which is otherwise known as the Net Primary Production (NPP tons ha^{-1}), is calculated by subtracting the stand respiration from the GPP (Landsberg & Sands, 2010). The NPP is then allocated to various tree components such as the foliage, stems, and roots (Figure 4). The biomass of individual tree components is calculated by adding the allocated NPP to the initial biomass.

The implementation of tree mortality in the 3-PG model is based on the concept of age-dependent probability of tree death. It also accounts for mortality caused by long-term stress factors such as water stress, pests, and diseases. Changes in stocking are modelled using the -3/2 power law (Landsberg & Sands, 2010; Drew & Flewelling, 1977). Detailed descriptions of the sub-models and the basic equations used have been published (Landsberg & Sands, 2010; Almeida *et al.*, 2009; Sands, 2004; Coops *et al.*, 1998; Landsberg & Waring, 1997; Pérez *et al.*, 1994).

3.3.2 Data inputs

The data inputs required for simulation with 3-PG are classified in to three types:

- *Climate data*- Total monthly incoming solar radiation (million J m^2 day^{-1}); monthly averages of daily maximum temperature (^oC) and daily minimum temperature (^oC); the total monthly rainfall (mm) and number of frostdays ($month^{-1}$); the daytime atmospheric Vapour Pressure Deficit (VPD; mbar) and the atmospheric CO_2 concentration (ppm).
- *Site-specific data*- inputs required for site description are site latitude (^oN), site fertility rating, maximum available soil water (mm), and soil texture.
- *Time series data*- inputs required to define the initial conditions of a stand are dry biomass (tons ha^{-1}) of foliage, stem including branches and bark, and roots; stocking density; and current available soil water (mm).

3.3.3 Data outputs

The outputs obtained from the 3-PG model are stand evapo-transpiration, Net Primary Production (NPP), Specific Leaf Area (SLA) and Leaf Area Index. Other output forms that are more familiar to forest managers, such as standing volumes, mean annual increment (MAI) and mean dBH are derived using allometric relationships (Landsberg & Sands, 2010).

3.4 The 3PG-Heureka model

The hybrid 3PG-Heureka model combines the simplified process-based carbon balance model 3-PG (Landsberg & Sands, 2010) and the empirically-based forest management model Heureka-Regwise (Fahlvik *et al.*, 2014; Wikström *et al.*, 2011). The 3-PG component is used to predict forest growth based on the total stand biomass increment, while the Heureka-Regwise component is used to predict mortality and the impact of management activities. The model can be parameterized for even- and uneven-aged stands of coniferous and broadleaved species in Sweden.

3.4.1 Basic concept of the 3PG-Heureka model

The 3PG-Heureka model has six major sub-models and an input-output module that connects the model software to the input and results database. Its sub-models are:

1. Sub-model for estimating individual tree height at the start of the simulation
2. Sub-model for estimating individual tree biomass

3. Sub-model for estimating five-year individual tree level basal area and height increments
4. Sub-model for estimating mortality and predicting management impact
5. Soil-water balance sub-model
6. Biomass production sub-model

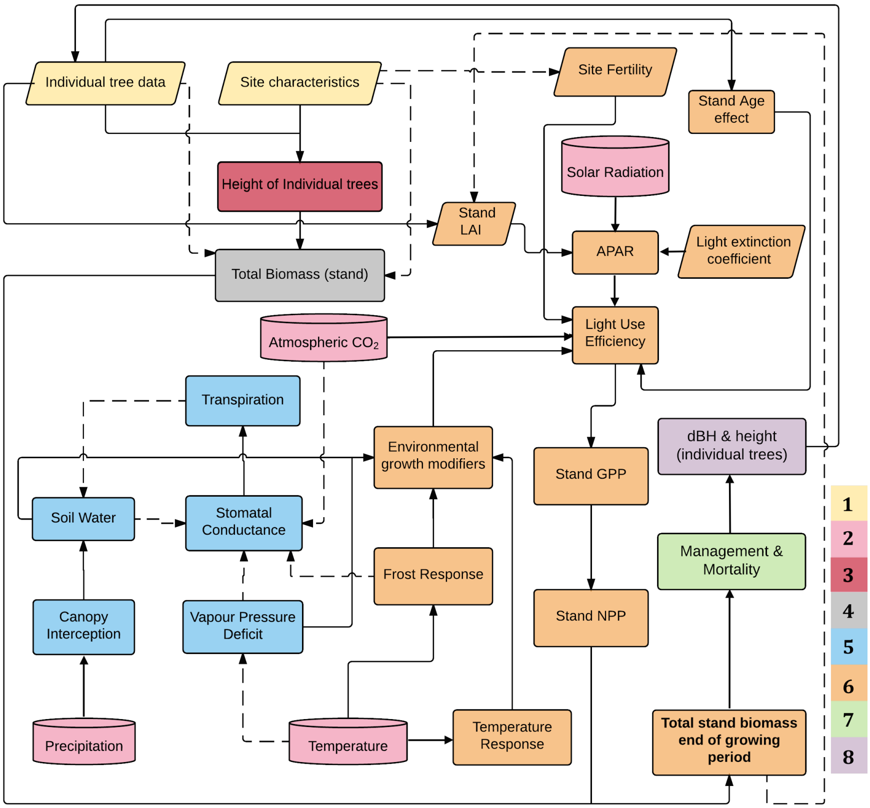

Figure 5. Schematic representation of the 3PG-Heureka model. The colours show the different model components and sub-models: (1) Initial stand and site input data, (2) Climate data, (3) Sub-model for estimating individual tree height at the start of the simulation, (4) Sub-model for estimating individual tree biomass, (5) Soil-water balance sub-model, (6) Biomass production sub-model, (7) Sub-model for estimating mortality and the impact of management activities in a plot. (8) Sub-model for estimating five-year increment of dBH and height of individual trees. Solid lines indicate direct relationship and dotted lines indicates indirect relationship.

The first four sub-models were taken from the Heureka-Regwise and last two were adapted from 3-PG (Figure 5). The 3-PG biomass production sub-model is designed to work at stand-level. Therefore some modifications were necessary to adapt it to work at a landscape-level as required in the 3PG-Heureka model.

3.4.2 Modifications of the biomass production sub-model

The biomass production sub-model was originally designed for stand-level simulation. Therefore some modifications were done so that it could be used at the landscape-level. Specifically, the procedures for computing the *fcc*, SLA and age modifier were altered.

Table 1. Specific Leaf Area (SLA; $m^2\ kg^{-1}$) values for various tree species. H_{mean}= mean stand height (dm).

Tree species	**SLA ($m^2\ kg^{-1}$)**		
	H_{mean} < 80	200 <H_{mean} < 80	H_{mean} > 200
Scots pine	4.5	-0.0067 H_{mean}+5.0333	3.7
Norway spruce	5	-0.1 H_{mean} +5.8	3.8
Birch	13	-0.1 H_{mean} +13.8	11.8

The *fcc* was calculated by assuming a linear increase of canopy cover with stand age until the stand attains full canopy cover (Equation 1; Landsberg & Sands, 2010), which was assumed to occur (*fcc*= 1) at a stand basal area of 20 $m^2\ ha^{-1}$. The stand LAI was calculated from the biomass of foliage and Specific Leaf Area (SLA). The stand SLA peaks at the start of stand development and subsequently decreases with stand age (Weiskittel *et al.*, 2008; Bond-Lamberty *et al.*, 2002). It also varies with the position of the foliage in the canopy (Weiskittel *et al.*, 2008) and, in the case of Scots pine and Norway spruce trees of the same age, with size characteristics such as height and diameter (Xiao *et al.*, 2006; Hager & Sterba, 1985). Therefore, using the mean tree height as a predictor of the SLA allows one to account for its variation with respect to both stand age and canopy position. The SLA was assumed to be constant for young stands (mean height <8m) and old stands (mean height >20 m). For middle-aged stands (mean stand height 8m-20m), the SLA decreased as the stand height increased (Table 1). The age modifier function was altered to suit boreal tree species (Equation 2); the values of age_{max} used in the simulations were 500, 300 and 200 for Scots pine, Norway spruce and Birch stands, respectively. The value of age_{Rel} used in the simulations was 0.65.

$$fcc_y = 0.05age - 0.05 \tag{1}$$

$$a_{mod}=\frac{1}{1+\left[\frac{\left(age/age_{\max}\right)^{0.55}}{age_{Rel}}\right]^{n_{age}}} \quad (2)$$

where fcc_y=fractional canopy cover for young stands (stand basal area less than 20 m^2 ha^{-1}). For stands basal area more than 20 m^2 ha^{-1} fcc=1. a_{mod}=stand age modifier, age=stand age (years), age_{max}= stand longevity (years), age_{Rel}=relative age of stand when a_{mod} is 0.5, n_{age}=strength of the response curve.

3.4.3 Growth simulation with the 3PG-Heureka model

In the 3PG-Heureka model, the initial heights of individual trees are estimated using functions developed by Söderberg (1992). The whole tree biomass of individual trees is then calculated using biomass functions for individual tree species (Figure 5; Table 2). The whole tree biomass of individual trees in a plot is summed to obtain stand-level biomass values of the plot. Similarly, the stand-level foliage biomass is calculated using biomass functions (Table 2). The stand LAI is calculated from foliage biomass (Landsberg & Sands, 2010), after which the stand-level monthly NPP is calculated using the biomass production sub-model for each plot as explained in section 3.3.1. This value is then added to the initial stand-level whole tree biomass for the month in question to obtain the initial whole tree biomass for the next month. This process is performed iteratively 60 times to obtain the five year stand-level whole tree biomass increment.

Table 2. *Functions used in individual tree biomass sub-model for various tree components and tree species.*

Functions used in individual tree biomass sub-model	**Source**
Mature trees (dBH >10 cm)	
Above ground biomass	Marklund (1988)
Below ground biomass	Petersson and Ståhl (2006)
Foliage biomass Norway spruce and Scots pine	Marklund (1988)
Foliage biomass Birch	Repola (2008)
Young trees (dBH≤10 cm)	
Biomass above ground	Claesson *et al.* (2001)
Biomass below ground	Claesson *et al.* (2001)
Foliage biomass	Claesson *et al.* (2001)

The stand-level basal area after five-years is calculated from the stand-level whole tree biomass after five-years using a linear regression function (Subramanian *et al.*, 2016b). In the 3PG-Heureka model, the stand LAI is updated once per year. However, the function for allocating NPP to individual tree components is not currently implemented in the 3PG-Heureka model. Therefore it is not possible to update the foliage biomass and LAI of the stand monthly. The foliage biomass was instead updated using a linear regression function that relates the stand-level whole tree biomass to stand-level foliage biomass (Subramanian *et al.*, 2016b).

In parallel, the five-year diameter growth of individual trees is estimated using individual tree growth functions (Elfving & Nyström, 2010). The individual trees' diameters are adjusted so that they sum to the estimated basal area estimated from the stand biomass (Subramanian *et al.*, 2016b). The five-year height increment of individual trees is estimated from their initial height using height growth functions for top-height trees. Afterwards, the height increment of individual trees is adjusted with a modifier that depends on the basal area of larger trees (Elfving & Nyström, 2010). In the 3PG-Heureka model, the basal area growth is calculated on the basis of physiological processes and climate data. The adjustment of individual trees' heights based on the individual tree basal area function was re-calibrated so that the tree height increment is also calculated based on physiological processes and climate data. This was done by running the Heureka-Regwise model for two periods while running 3PG-Heureka model for one period (Subramanian *et al.*, 2016b).

If the individual tree diameter in the 3PG-Heureka model at end of period 1 (dBH_{3pg1}) is greater than diameter of the same tree in the Heureka-Regwise model at the end of period 2 (dBH_{Elf2}), the height corresponding to dBH_{Elf2} is calculated using the 3PG-Heureka model for that particular tree. If the diameter in dBH_{3pg1} is greater than the dBH of the trees in period 1 estimated using the Heureka-Regwise model (dBH_{Elf1}) and less than dBH_{Elf2}, or if dBH_{3pg1} is less than dBH_{Elf1}, an interpolation function is used to estimate individual tree heights in the 3PG-Heureka model (Subramanian *et al.*, 2016b). If $dBH_{Elf1} < dBH_{3pg1} < dBH_{Elf2}$, the individual tree heights in the 3PG-Heureka model are estimated using Equation (3). Conversely, if $dBH_{3pg1} < dBH_{Elf1}$, the individual tree height is calculated using Equation (4). Management and mortality functions were adapted from the Heureka-Regwise model; management activities such as thinning, final felling, regeneration and soil preparation are simulated as described in section 3.2.4.

$$h_{3pg1} = \left[\frac{(d_{3pg1} - d_{Elf1})(h_{Elf2} - h_{Elf1})}{(d_{Elf2} - d_{Elf1})}\right] + h_{Elf1} \tag{3}$$

$$h_{3pg1} = \left[\frac{(d_{3pg1} - d_{Elf0})(h_{Elf1} - h_{Elf0})}{(d_{Elf1} - d_{Elf0})}\right] + h_{Elf0} \tag{4}$$

where h= individual tree height (dm), d= individual tree diameter (cm), $_{3pg1}$= variable simulated using 3PG-Heureka model at the end of period 1, $_{Elf0}$= variable simulated using Heureka-Regwise during period 0, $_{Elf1}$= variable simulated using Heureka-Regwise at the end of period 1 and $_{Elf2}$= variable simulated using Heureka-Regwise at the end of period 2.

3.4.4 Data inputs

The data inputs required for simulations with the 3PG-Heureka model are classified into three types:

- Climate data- Total monthly incoming solar radiation (R, Wm^{-2}); monthly averages of daily maximum temperature (T_{max}, K) and daily minimum temperature (T_{min}, K); the total monthly rainfall (ppt, mm); the atmospheric CO_2 concentration (ppm); and the number of frost days per month ($n_{frostdays}$, days $month^{-1}$).
- Site-specific data- inputs required for site description are site co-ordinates (latitude and longitude), altitude (m), Site Index (m; dominant height at a total stand age of 100 years), distance from coast (km), dominant tree species, soil moisture content (dry, moist, mesic moist or wet), maximum available soil water, soil texture and site productivity rating.
- Inputs required to define the initial conditions of the stand are dBH (mm), dBH increment in the last five years (d_5, 0.1 mm), and the tree species identity of individual trees. The most common time step used in the 3-PG model is 1 month whereas that for Heureka-Regwise is 5 years. Therefore, the basic time step of the 3PG-Heureka model is 5 years, corresponding to 60 iterations of the 3-PG model and one iteration of the Heureka-Regwise model.

3.4.5 Data ouputs

The outputs obtained from 3PG-Heureka model are individual tree variables such as height (dm), biomass (g $tree^{-1}$), dBH (mm) and age (years), along with stand variables such as mean height (dm), mean dBH (mm), stand density (trees ha^{-1}), mean age (years), biomass (tons ha^{-1}), standing volume (m^3 ha^{-1}) and NPP (tons Dry Mass ha^{-1}).

3.5 Simulation of a forest stand incorporating stochastic events using the Heureka-Standwise model (Paper I)

In this exercise, the empirical Heureka-Standwise model was used to simulate a Norway spruce stand incorporating interacting effects of stochastic adverse events associated with future climate change in southern Sweden. The stochastic events considered in this study were root rot infection, bark beetle damage, and storm events. The severity of infection and extent of damage caused by these events were assumed to increase as a result of future climate change. The combined effects of these stochastic events on a conventionally managed Norway spruce stand in southern Sweden were simulated under a changing climate with corresponding increases in the intensity of root rot infection, bark beetle damage and storm frequency. The annual increases in the incidence of root rot infection and bark beetle damages were assumed to be 1% each, and storms were assumed to occur once every 5th year under changing climate (Subramanian *et al.*, 2016a).

The reference management regimes implemented were based on current forest management programmes for Norway spruce stands in southern Sweden. The site index for Norway spruce was 34 m. The impact of stochastic events such as root rot infection, bark beetle damage and storm events on the forest's economic productivity was calculated based on its Land Expectation Value (LEV; € ha^{-1}). Two kinds of adaptive management strategy for reducing the risk of damages under the current climate and a climate change scenario were considered:

- Avoiding thinning and reducing the rotation length
- Replacing Norway spruce with other suitable tree species such as hybrid aspen, hybrid larch, European beech, or birch

The percentage change in LEV was calculated for both adaptation strategies and compared to that for conventional management of the Norway spruce stand. However, the stand's growth was predicted to be unaffected by climate change in this case. It was concluded that this inability to account for climate change occurred because the model used in the simulations was empirically based, and a process-based model is needed to simulate the growth and yield of forest stand under a climate change scenario.

3.6 Simulation of forest stands incorporating interacting effects of climate change and environmental pollution using the 3-PG model (Paper II)

In this exercise the Net Primary Production (NPP; KgC m^{-2} yr^{-1}) of Norway spruce, Scots pine and birch stands were simulated under a future climate scenario incorporating interacting the effects of climate change and changes in concentration of the environmental pollutant tropospheric ozone. A simple process-based stand-level model 3-PG was used for this purpose. This model requires the input of species-specific parameters. Values for these parameters were obtained from previous publications such as those by as Landsberg *et al.* (2005), Potithep and Yasuoka (2011) and Subramanian (2010) for Scots pine, birch and Norway spruce stands respectively. Additional input data for the 3-PG model such as the initial stand biomass data were obtained from the empirical model Heureka-Standwise. The initial biomass of foliage, root and stem (tons ha^{-1}) was simulated for all the three tree species in six representative forest stands located in six zones in Sweden (Figure 2) using Heureka-Standwise model.

The tropospheric ozone scenarios considered in this study were based on AOT40 concept (Karlsson *et al.*, 2004a; Wallin *et al.*, 2002). The current AOT40 values for each zone were obtained from the European Monitoring and Evaluation Programme (EMEP; D. Simpson, Norwegian Meteorological Institute, Personal Communication, 3rd January 2012) for the years 2005, 2006, 2008 and 2009, and the average AOT40 was calculated across these 4 years. This value was used to calculate the ozone dose-response relationship and to parameterize the 3-PG model to include ozone effects. Three ozone scenarios were considered:

- Pre-historic ozone scenario- the tropospheric ozone concentration was assumed to equal that in the pre-industrial period; AOT40=0 [i.e. the ozone concentration never exceeded 40 ppb)
- Ambient ozone scenario- current ozone levels in Sweden (from EMEP)
- Increased ozone scenario- a doubling of current ozone levels in Sweden ("Worst case")

3.6.1 Ozone parameterization in the 3-PG model

The adverse effect of ozone molecules on tree growth was computed on the basis of three different experiments with Open Top Chambers (OTCs) for conifers (Norway spruce and Scots pine; Skärby *et al.*, 1995; Wallin & Skärby, 1992) and birch (Uddling *et al.*, 2006; Karlsson *et al.*, 2003). In this experiment, OTCs containing potted saplings were treated with normal air (ambient ozone scenario), charcoal-filtered air (pre-historic ozone scenario) and air with twice the current ambient ozone concentration (increased ozone scenario), and the changes in the seedlings' growth patterns were analysed. The net photosynthesis at saturated Photosynthetic Photon Flux Density (PPFD) of shoots and chlorophyll content in the foliage were measured at the end of the growing season every year. The net photosynthesis at saturated PPFD was measured by analysing the gas exchange of the shoots and chlorophyll content in the foliage was measured by microscopy procedure (Skärby *et al.*, 1995). The gas exchange and microscopy sampling were separately conducted for different age class of foliage. Thereafter the reduction in net photosynthesis and chlorophyll content due to unit increase in ozone concentration (AOT40) was calculated.

Table 3. *The percentage changes in two growth parameters (maximum photosynthesis rate and accelerated senescence), per unit increase in Accumulated Ozone exposure above Threshold concentration of 40 parts per billion (AOT40; Δ). Ozone correction factors are reported separately for each zone, taking the values for pre-historic ozone scenario as 1 in each case.*

		Deciduous trees		**Conifer trees**	
		Maximum photosynthesis rate	*Accelerated senescence*	*Maximum photosynthesis rate*	*Accelerated senescence*
Δ*		-0.24	+0.2	-1.0	+5.0
Ozone scenario	***Zone***				
Ambient ozone	1	0.97	1.03	0.86	1.14
	2	0.97	1.03	0.87	1.13
	3	0.97	1.03	0.86	1.14
	4	0.98	1.02	0.91	1.09
	5	0.98	1.01	0.93	1.07
	6	0.99	1.01	0.96	1.04
Increased ozone	1	0.96	1.03	0.83	1.12
	2	0.97	1.02	0.85	1.11
	3	0.96	1.02	0.84	1.12
	4	0.98	1.02	0.90	1.08
	5	0.98	1.02	0.92	1.07
	6	0.99	1.01	0.96	1.04

*= Percentage change in growth parameter per unit increase of AOT40 ozone exposure

The maximum photosynthetic capacity of the canopy and leaf/needle senescence (which reduces photosynthetic capacity over time) were both identified as being important for forest growth and sensitive to the ozone concentration in a way that was possible to implement in the 3-PG model (Subramanian *et al.*, 2015). The maximum photosynthetic rate (net photosynthesis at saturated PPFD) from the OTC measurements can be likened to the canopy quantum efficiency (photosynthetic quantum yield) parameter in the 3-PG model (Landsberg & Sands, 2010). Ozone accelerates the life cycle of leaves by reducing its chlorophyll content and promotes leaf/needle senescence (Schelhaas *et al.*, 2003; Skärby *et al.*, 1995). Canopy leaf/needle senescence is analogous to accelerated senescence. Therefore, the percentage changes in growth parameters such as the maximum photosynthetic rate and the accelerated rate of senescence per unit increase in AOT40 ozone exposure were derived for each zone from OTC experiments, and the reductions in these parameters under the ambient and increased ozone scenarios relative to the pre-historic ozone scenario were calculated separately for conifers and birch (Table 3; Subramanian *et al.*, 2015).

3.6.2 Simulation of NPP using the 3-PG model including interacting effects of climate and ozone

Two future climate scenarios A2 and B2, based on Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) and a reference climate scenario, were used in this study (Pachauri & Reisinger, 2008; Nakicenovic *et al.*, 2000). Climate data were obtained from the Swedish Meteorological and Hydrological Research Institute (SMHI, 2016). The atmospheric CO_2 concentration for the reference climate scenario was 390 ppm; for the A2-scenario it was 850 ppm; and for the B2-scenario, it was 600 ppm (Albritton *et al.*, 2001).

The NPP was simulated for six representative stands (Figure 2) using the 3-PG model for the year 2011 (reference climate scenario and ambient ozone scenario). For the year 2100, two climate scenarios (A2 and B2) along with two ozone scenarios (ambient and increased) were considered (Figure 6). To analyse the impact of interacting effects of tropospheric ozone and climate change on vegetation growth, the change in annual NPP under future climate scenarios and ozone scenarios during the year 2100 was compared to the annual NPP in the reference climate scenario and ambient ozone scenario during the year 2011.

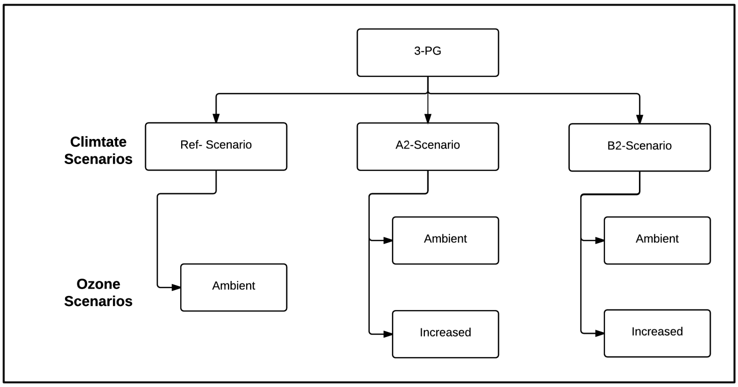

Figure 6. Outline of the process for performing simulations with the 3-PG model.

The 3-PG model is a stand-level model. However, to analyse the impact of climate change on the management of Swedish forests, it is important to analyse growth at the landscape-level.

3.7 Simulation of a forest landscape incorporating interacting effects of climate change and weather extremes using the 3PG-Heureka model (Paper III & IV)

A forest landscape was simulated using the 3PG-Heureka hybrid model, incorporating the interactive effects of climate change and weather extremes such as storm events. The initial tree data used for the 3PG-Heureka model was NFI data from permanent sample plots in Kronoberg county, Sweden, covering the years 2008-2012. This NFI dataset was used for model parameterization and evaluation, and also as a source of starting values for the simulations. The climate data used in the study were obtained from the Rossby centre at the Swedish Meteorological and Hydrological Institute (SMHI). The climate data on total monthly precipitation (ppt); monthly averages of daily maximum temperature (T_{max}, K) and daily minimum temperature (T_{min}, K); total monthly incoming solar radiation (R, Wm^{-2}) and number of frost days per month ($n_{frostdays}$) were gridded, with a spatial resolution of 12 X 12 km^2 (SMHI, 2016). The climate data for each NFI plot were assumed to be identical to those for the grid cell whose centre was closest to that of the NFI plot in question (Figure 7). The monthly global mean atmospheric CO_2 concentration in parts per million (ppm) was obtained from the Earth System Research Laboratory (ESRL) Global Monitoring Division (Dlugokency *et al.*, 2015).

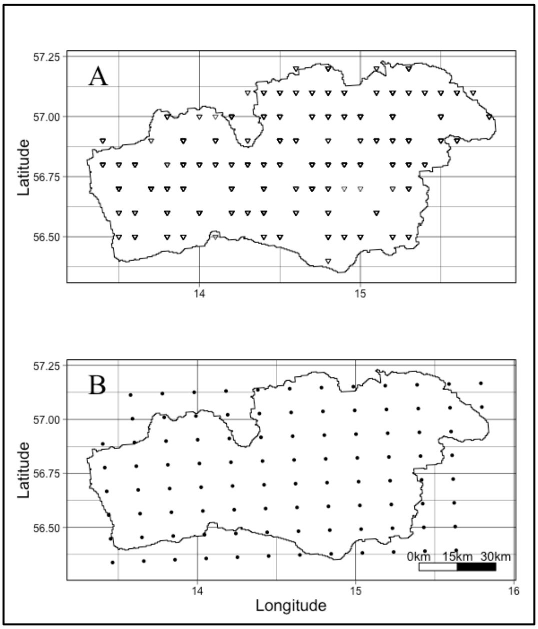

Figure 7. Map showing the geographical locations of NFI plots (A) and climate data observation points (B) in Kronoberg county (Subramanian *et al.*, 2016b).

Three climate scenarios were considered: two future climate scenarios and one historic climate scenario. The historic climate scenario was modelled by performing a 3PG-Heureka simulation using observed historic climate data that were converted into the gridded format by interpolating using the Mesoscale Analysis (MESAN) model (Hāggmark *et al.*, 2000). Historical climate data covering a 22-year period from 1989-01-01 to 2010-12-31 were used for model parameterization and evaluation (Paper III). Two different future climate scenarios adopted from the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) were considered, namely the RCP8.5 and RCP4.5 Representative Concentration Pathways (IPCC, 2013; Moss *et al.*, 2010). Scenario data were available from 2010-01-01 to 2100-12-31 (91 years). A reference run using repeated historic climate data was also simulated for the same time period (i.e. 2010-01-01 to 2100-12-31). This was used to predict the behaviour of the forest landscape under a future climate (Paper IV).

3.7.1 Parameterization of the 3PG-Heureka model (Paper III)

The 3-PG component of the 3PG-Heureka model require certain species-specific parameters. Most of these aside from the site productivity modifier were obtained from the literature reviews performed in the course of the previous studies. The coefficients of the age modifier function (equation 2) were modified slightly to avoid over-estimation of growth in very old stands.

Parameterization of the site productivity modifier

The site productivity modifier is scaled according to the site's ground vegetation type, using scaling factors ranging from -5 (low fertility) to 4 (high fertility; Elfving & Nyström, 2010). The resulting scaled vegetation type index values were used as the input variable in the site productivity modifier function. The stand-level whole tree biomass (tons ha^{-1}) was simulated using the Heureka-Regwise model for a 22-year time period, using the NFI 2008-2012 data as the starting values. This was taken as the baseline simulation. Then, the stand-level whole tree biomass (tons ha^{-1}) for the same time period and NFI plots was simulated using the 3PG-Heureka hybrid model using historic climate data (1989-2010). The mean whole tree biomass for each vegetation type index class was calculated, after which the residual percentage for the whole tree biomass was calculated and plotted against the vegetation type index (Subramanian *et al.*, 2016b). Simulations with the 3PG-Heureka model were repeated with different values of the site productivity modifier function's coefficients until the model's output was sufficiently similar to the results of the baseline simulation. Once the variation in the residual plot has been minimized, the coefficients for the site fertility modifier function were fixed.

A polynomial function for the site productivity modifier using the scaled index value of ground vegetation type as the input factor was used in the model for calculating site fertility modifier (Equation 5). Separate functions were used for Scots pine, Norway spruce and birch stands (Table 4).

Table 4. *Coefficients used in calculation of site productivity modifier function.*

Coefficient	**Scots pine**	**Norway spruce**	**Birch**
a	0.38	0.53	0.37
b	0.036	0.0528	0.013
c	0.0013	0.0032	0.004

$$Fr_{mod} = a + bx + cx^2 \quad (5)$$

Where x= scaled index value of ground vegetation type (Elfving & Nyström, 2010)

3.7.2 Evaluation of the 3PG-Heureka model (Paper III)

The predictive capacity of the 3PG-Heureka model was evaluated by comparing the age-dependent stand variables simulated using the 3PG-Heureka model with the baseline simulation. The age-dependent stand variables used for this purpose were: mean whole tree biomass (tons ha^{-1}), mean basal area (m^2 ha^{-1}), mean basal area weighed height (m) and mean stand density (trees ha^{-1}) for the time period 1989-2010. The residual content (%) in 3PG-Heureka predictions was calculated by comparing them to the baseline simulation in order to analyse the hybrid model's predictive ability and behaviour.

3.7.3 Simulation of a forest landscape incorporating interactive effects of climate change and weather extremes and different management regimes (Paper IV)

In addition to the three climate scenarios (the historic climate scenario and the future climate scenarios RCP4.5 and RCP8.5), four different management regimes were considered (Figure 8): Business as usual (BAU), Business as usual + Storm (BAU+Storm), Shorter rotation length (SR), and Promoting alternative tree species (PAS). Details of the concepts, assumptions and key input parameter values used in the 3PG-Heureka model for each regime are presented in the corresponding publication (Subramanian *et al.*, 2016c).

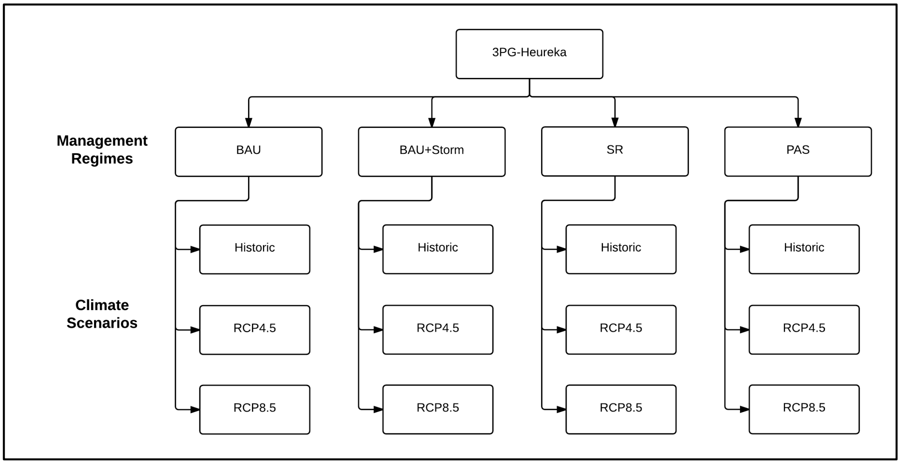

Figure 8. Schematic representation of the 3PG-Heureka simulations under the Historic, RCP4.5 and RCP8.5 climate scenarios for four different management regimes: Business as usual (BAU), Business as usual + Storm (BAU+Storm), Shorter rotation length (SR) and Promoting alternative tree species (PAS).

Simulation of annual volume increment, annual net revenue obtained and storm-felled volume under different management regimes and climate scenarios in Kronoberg county

The 3PG-Heureka model was used to estimate the annual volume increment (million m^3 yr^{-1}), annual net revenue obtained (billion SEK yr^{-1}), and storm-felled volume (million m^3) for each combination of management regime and climate scenario in the Kronoberg landscape over the time period 2010-01-01 to 2100-12-31. The simulated variables were plotted as functions of the time in years, and the results for the BAU+Storm scenario in each climate scenario were compared to those for the BAU regime to analyze the combined impact of climate change and extreme weather events on the productivity and economic performance of the forest landscape (Figure 8). Then, the results obtained under each climate scenario for the SR and PAS management regimes were compared to those for the BAU+Storm regime to analyze how the adverse effects of extreme weather events could be mitigated by adopting alternative management programmes as part of an adaptive strategy.

4 Main results

4.1 Impact of root rot, bark beetles and major storm events on the land expectation value of forest stands under current climate and future climate (Paper I)

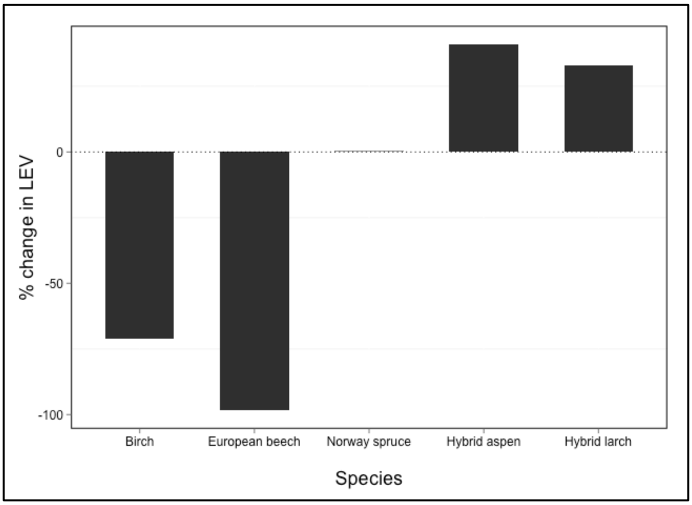

Figure 9. Percentage changes in Land Expectation Value (LEV) for un-thinned Norway spruce stands with shorter rotations, and planting alternative tree species plantations such as hybrid larch, hybrid aspen, European beech and birch in southern Sweden in comparison to conventionally managed Norway spruce plantation. The values for hybrid aspen are based on four 25-year rotation periods.

Economic productivity calculations based on percentage changes in Land Expectation Value (LEV) indicated that alternative management programmes based on planting European beech and birch would reduce volume production and be less profitable than programmes based on planting other tree species (Figure 9). In contrast, both hybrid aspen and hybrid larch plantation would apparently be more profitable than Norway spruce cultivation. Cultivation of un-thinned Norway spruce stands with shorter rotation would be at least as profitable as conventional Norway spruce cultivation.

4.2 Impact of interacting effect of tropospheric ozone and climate change on NPP of important tree species in Sweden (Paper II)

The percentage change in simulated annual NPP (Kg C m^{-2} yr^{-1}) for the ambient and increased ozone scenarios under the A2 and B2 climate scenarios during the year 2100 was calculated and compared to the simulated annual NPP under the reference climate and ambient ozone scenario during the year 2011 (Figure 10). Climate change caused the NPP to increase by 56.4-84% (A2-scenario) or 18.8-44% (B2-scenario) for Norway spruce; 45.1-89.2% (A2-scenario) or 18.8- 48.2% (B2-scenario) for Scots pine and 48-105.7% (A2-scenario) or 21.2-54.3% (B2-scenario) for birch by the year 2100. If the tropospheric ozone concentration increases in parallel with climate change, the NPP is still predicted to increase for all tree species relative to that under the reference climate scenario. However, the magnitude of the increase will be smaller than would otherwise be the case. The reduction in NPP due to increased tropospheric ozone concentrations was more pronounced in conifers than in birches (Table 5). In addition, the ozone effect was most pronounced in southern Sweden (Zones 1-3; Figure 10).

Table 5. *The percentage reduction in Net Primary Production (NPP; Kg C m^{-2} yr^{-1}) in future climate scenarios (A2 and B2) when the concentration of tropospheric ozone is twice the current ambient level.*

Tree species	**% Reduction in NPP due to increase in tropospheric ozone**	
	A2-scenario	*B2-scenario*
Norway spruce	4 - 27.8	6 - 21.1
Scots pine	8.9 - 28.8	7.1 - 25.9
Birch	2.8 - 8.8	2.8 - 7.0

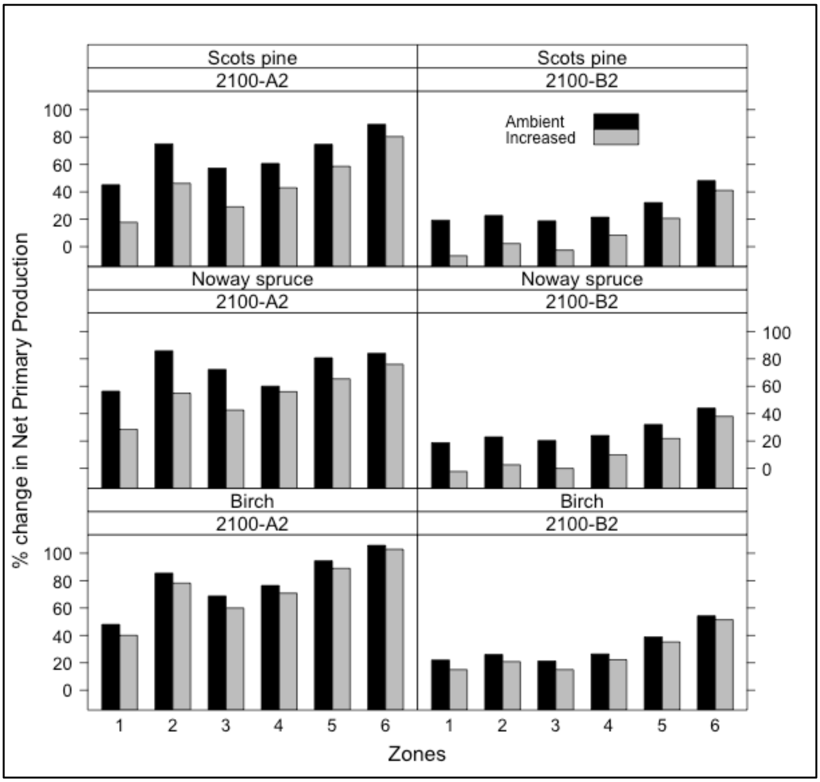

Figure 10. Percentage changes in Net Primary Production (NPP; Kg C m^{-2} yr^{-1}) of Scots pine, Norway spruce and birch in the future climate scenarios (A2 and B2) and the ambient ozone scenario during the year 2100, relative to the reference climate scenario and ambient ozone scenario during the year 2011. The figure also shows the change in NPP (%) for future climate scenarios A2 and B2, if the concentration of tropospheric ozone increases twice the ambient level (increased ozone scenario).

4.3 Evaluation of the 3PG-Heureka hybrid model (Paper III)

Stand variables such as the mean whole tree biomass (tons ha^{-1}), mean stand basal area (m^2 ha^{-1}), mean basal area weighed height (m) and mean stand density (trees ha^{-1}) simulated using 3PG-Heureka hybrid model were compared to a baseline simulation using the Heureka-Regwise model, and the residuals (%) were plotted against the age class of forest stands (Figure 11). The model underestimated the mean whole tree biomass of middle aged Scots pine and Norway spruce stands in the 41-60 age-class, and overestimated the mean whole tree biomass for young stands in the 0-20 age class for all tree species (Figure 11). The average residual content (%) in the model's whole tree biomass predictions over the entire simulation period was -1.13% for Scots pine, -0.02% for Norway spruce and -0.67% for birch. Similar distributions of residuals were observed for other stand variables too (Figure 11). In addition the hybrid model underestimated the mean basal area weighed height of young stands in the age class 0-20.

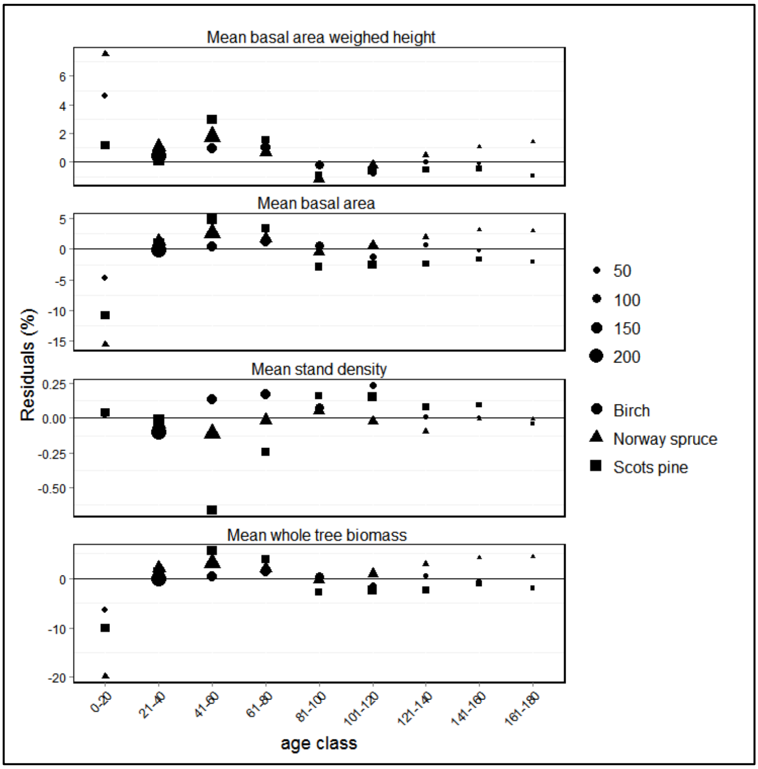

Figure 11. Comparison of stand variables such as mean basal area weighed height (m), mean stand basal area (m^2 ha^{-1}), mean stand density (trees ha^{-1}) and mean whole tree biomass (tons ha^{-1}) of Scots pine, Norway spruce and birch for the period 1989-2010 as predicted by simulations using the 3PG-Heureka hybrid model and as predicted by the baseline Heureka-Regwise simulation. The residuals (%) in each case were plotted against the age class of the stand and the number of observations for each age class is indicated by the size of the dots.

4.4 Simulated forest growth, economic outcomes and damages in Kronoberg landscape incorporating interactive effects of climate and stochastic weather extremes (Paper IV)

The annual volume increment increased over time under all three climate scenarios and all management regimes (Figure 12). By the end of the simulation period (2080-2100), the average annual volume increment for the Business as usual (BAU) regime was 8.6% and 21% higher, respectively, under the RCP4.5 and RCP8.5 future climate scenarios, compared to the historic climate scenario. Under the management regimes Business as usual + Storm (BAU+Storm), Promoting alternative tree species (PAS) and Shorter rotation length (SR) management regimes, the annual volume increment was much lower than under the BAU regime because of the storm events included in the former cases.

The storm event during the year 2065 was of similar magnitude as the storm "Gudrun" which hit southern Sweden in the year 2005 and also the strongest storm event in this study. This storm reduced the annual volume increment in the BAU+Storm regime by approximately 7%, 9% and 12% for the historic, RCP4.5 and RCP8.5 scenarios, respectively (Figure 12). A similar trend was observed for PAS regime. However, the reduction in simulated annual volume increment was minimal in management regime SR scenario under all climate scenarios when compared to BAU+Storm and PAS regimes.

Similar trend was also found in annual net revenue obtained from Kronoberg landscape. Annual net revenue was reduced by storm events in all climate scenarios under BAU+Storm, PAS and SR regimes (Figure 13). The storm event in 2065 reduced the annual net revenue obtained under the management regime BAU+Storm by 56.7% (RCP4.5) and 41.8% (RCP8.5) in the future climate scenarios than the net income obtained in 2060. Similarly, the annual net revenue under PAS regime was reduced by 78.8% (RCP4.5) and 64.1% (RCP8.5) by the storm event in the year 2065 when compared to the annual net income obtained during 2060. Interestingly, however, the reduction in annual net revenue by storm event was lower under the SR management regime. The annual net revenue obtained in SR regime was only reduced by 19.3% (RCP4.5) and 12.4% (RCP8.5) during the storm event in the year 2065 when compared to the net annual income obtained during 2060. Similar trend was also found during other storm events.

The highest simulated storm-felling was found during the storm event in the year 2065 (Figure 14). Storm-felled volume was higher in future climate scenarios (RCP4.5 and RCP8.5) when compared to historic climate scenarios under all management regimes. The storm event during 2030 and 2095 were of similar intensity, however the storm-felling was more during 2095 especially under future climate scenarios.

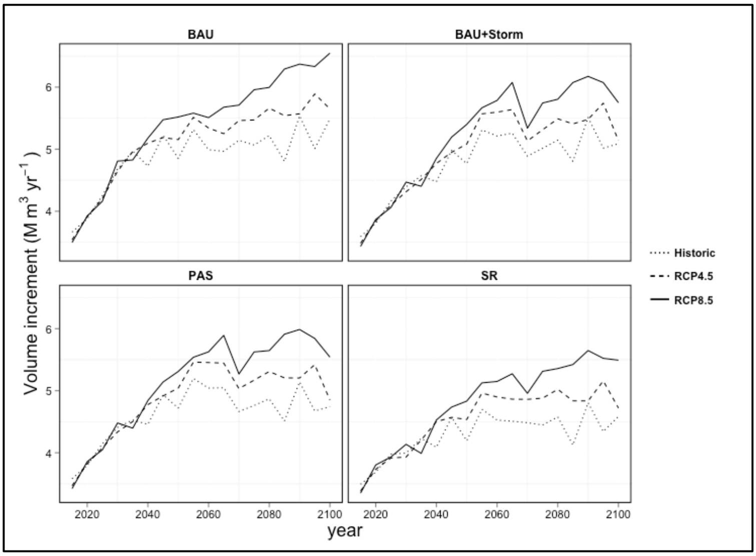

Figure 12. Predicted annual volume increments (million m^3 yr^{-1}) in Kronoberg county for different climate scenarios and management regimes. The regimes are Business as usual (BAU), Business as usual + Storm (BAU+ Storm), Promoting alternative tree species (PAS), and Shorter rotation length (SR). The climate scenarios are historic climate, and two future climate scenarios (RCP4.5 and RCP8.5).

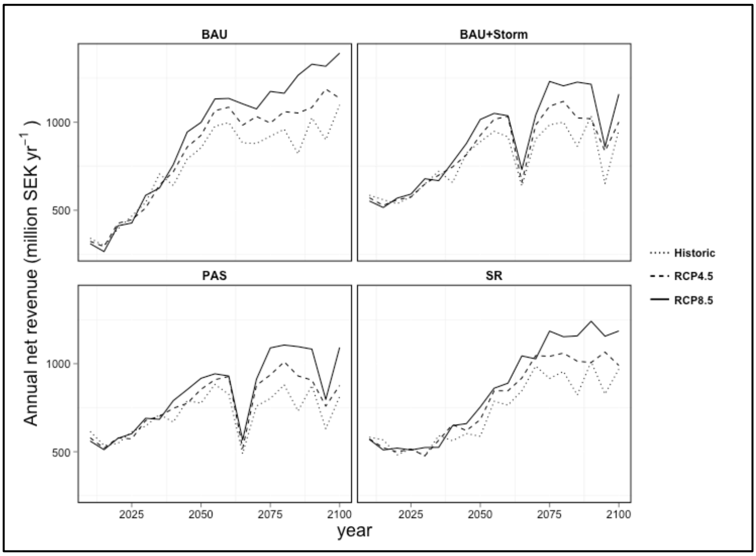

Figure 13. Predicted annual net revenue (million SEK yr^{-1}) in Kronoberg county for four different climate scenarios and management regimes. The regimes are Business as usual (BAU), Business as usual + Storm (BAU+ Storm), Promoting alternative tree species (PAS), and Shorter rotation length (SR). The climate scenarios are historic climate, and two future climate scenarios (RCP4.5 and RCP8.5).

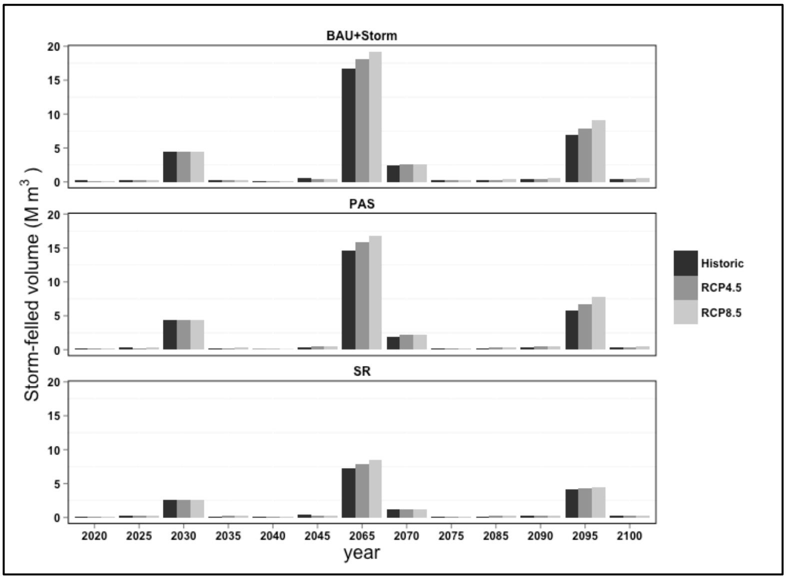

Figure 14. Predicted storm-felled volume (million m^3) in Kronoberg county for three different climate scenarios and management regimes. The regimes are Business as usual + Storm (BAU+Storm), Promoting alternative tree species (PAS), and Shorter rotation length (SR). The climate scenarios are historic climate, and two future climate scenarios (RCP4.5 and RCP8.5).

5 Discussion

5.1 Evaluation of different modelling approaches

The production and economic performance of Swedish forests under a changing climate were analysed using three different modelling tools: the empirical Heureka Decision Support System (DSS; Paper I), the process-based 3-PG model (Paper II), and the hybrid model 3PG-Heureka (Paper III and IV). The main advantage of the Heureka-DSS is that it requires a minimal number of input parameters to perform simulations, with no need to parameterize the model for individual tree species and sites. However, other models like 3-PG and 3PG-Heureka require several input model parameters. 3-PG is a stand-level model and it needs certain species-specific input parameters. In addition, it must be parameterized and calibrated for individual stands. Conversely, 3PG-Heureka is a landscape-level model and the 3-PG part in this model needs a much smaller number of readily available input parameters. However, it still needs to be parameterized and calibrated.

5.1.1 Evaluation of the 3PG-Heureka model predictions

The 3PG-Heureka model's predictions of age-dependent stand variables such as whole tree biomass, mean basal area weighed height, mean stand density and mean basal area were relatively fair (Figure 11; Paper III). The whole tree biomass and mean basal area of middle aged stands (age class 41-60) were underestimated because of the model's age modifier function (Equation 2). In addition, the mean basal area weighed height of young stands (age-class 0-20) was underestimated because the model overestimated the mean basal area for such stands (Figure 11).

5.2 A SWOT analysis of different modelling approaches

Strengths

- The cumulative effects of various risk factors associated with climate at stand-level (Paper I) were calculated by evaluating the proportion of trees affected by each factor and then summing these percentages. The methodology used in this work is simple and easy to understand.
- Hybrid modelling approaches could reduce the uncertainties in long-term forest planning. Therefore, the hybrid 3PG-Heureka model is better suited for long-term planning than the empirically-based Heureka-DSS.
- Hybrid modelling also allows the user to generate and test alternative management regimes and climate scenarios and formulate long-term landscape-level management strategies under changing environmental conditions.
- The initial data used in the simulations presented in this thesis were obtained from readily available NFI data sets. Consequently, such analyses are relatively quick to perform, which is very important for future planning.

Weaknesses

- The 3-PG and 3PG-Heureka models require some species-specific input parameters that may be unavailable to forest managers. Although the 3PG-Heureka model requires fewer such input parameters than the 3-PG model, some of them could still be difficult for forest managers to obtain.
- The 3-PG and 3PG-Heureka models must both be parameterized and calibrated using observed data before performing simulations, so the results of this study cannot be extended to different site and stand conditions. Moreover the parameterization was done by tuning most of the input parameters, so the analysis may retain significant uncertainties.
- The interactive effects of climate change and tropospheric ozone were studied using experimental data for tree saplings and the results were extrapolated to mature trees. Different results may have been obtained using experimental data relating to mature trees.
- The ozone parameterization in the 3-PG model was done by altering the canopy quantum efficiency parameter. While the experimental results were from net photosynthesis measured under saturated Photosynthetic Photon Flux Density (PPFD). This approach could have overestimated the impact of tropospheric ozone.
- The cumulative stand-level effects of risk factors such as root rot infection, bark beetles, and storm damage associated with future climate on forests' productivity and economic performance were analysed using the empirical

Heureka-DSS model, which cannot account for the increased growth due to climate change.

Opportunities

- The interactive effects of climate change and environmental pollutants such as tropospheric ozone on forest growth and biomass production were analysed using an ozone-parameterized 3-PG model. This approach could be extended to other environmental pollutants including CFCs, methane, and nitrous oxides, and to other geographical areas where environmental pollution is a bigger problem.
- The 3PG-Heureka model was parameterized and calibrated only for Kronoberg landscape. To make this model a general national-level planning tool, it would have to be parameterized for every county in Sweden. Further development of the model is required.
- The conclusions regarding the interactive effects of climate change and extreme weather events at the landscape-level were only based on analyses of a single risk factor – storm events. Future studies could incorporate other risk factors such as root rot, bark beetles, and pine weevils.
- The 3PG-Heureka model evaluates site productivity using a polynomial function whose solve input factor is a scaled ground vegetation type index. This function could be replaced with a process-based soil carbon model (e.g. CENTURY4.0, YASSO07), which may increase the model's accuracy.

Threats

- The 3PG-Heureka model underestimated the stand-level whole tree biomass of middle aged stands and the mean basal area weighed height of young stands. This error should be taken into account before formulating management plans based on the model's output.
- The allocation of carbon to individual tree components in 3PG-Heureka is based on empirical functions. Therefore, the allocation of biomass to individual tree components remains the same under a changing climate, which could lead to minor errors in the model's predictions.
- The interactive impacts of damage caused by storms, root rot and bark beetles were analysed at the stand-level, and the effects of storms together with climate change were analysed at the landscape-level. However, climate change could affect many other risk factors, such as summer frosts, pine weevils, snow damage and forest fires. The adaptive strategy proposed in this study will not necessarily be effective against all of these.

- The interactive effects of climate change and weather extremes like storms were evaluated on the basis of historic storm events, which were assumed to recur with the same wind speeds and frequencies as in the past. This assumption is questionable, so further analysis is required before implementing an adaptation strategy based on the results of this study.
- Some of the functions used in the 3PG-Heureka model (e.g. the functions for estimating the LAI from the stand-level whole tree biomass, and the stand basal area from the stand-level whole tree biomass) should only be used at the landscape-level and could introduce error if used at the stand-level.

5.3 Impacts of climate change on growth and biomass production of Swedish forests

Climate change was predicted to increase both growth and subsequent biomass production for all tree species under consideration (Paper II & IV). This was mainly due to increased temperatures and atmospheric CO_2 concentrations as well as longer vegetation periods, which enabled the trees to utilize more solar radiation for photosynthesis. The growth and biomass production predictions obtained using the process-based stand-level 3-PG model (Figure 10) and the landscape-level hybrid model 3PG-Heureka (Figure 12) were similar with this respect.

5.4 Impacts of interactive effects of climate change and tropospheric ozone on growth and biomass production of Swedish forests

Although the changing climate increased the growth and biomass production of important tree species in Sweden, the 3-PG model's predictions showed that increases in the tropospheric ozone concentration caused the increase in biomass production to be lower than it would otherwise have been for all tree species under consideration (Figure 10). For birch stands at all of the considered sites, the reduction in biomass production due to the doubling of the tropospheric ozone concentration on going from the ambient ozone scenario to the increased ozone scenario was much smaller than the increase due to climate change (Table 5; Figure 10). More pronounced reductions in biomass production due to increasing ozone concentrations were observed for Norway spruce and Scots pine stands in southern Sweden, but the reduction for these species was less pronounced in central and northern sites. Therefore, environmental pollutants such as tropospheric ozone are not predicted to pose a significant threat to Swedish forests in future relative to other risks associated with climate change such as root rot infection, bark beetles, and storm damage.

5.5 Management measures implemented as adaptation strategies against various risk factors associated with climate change

Management activities such as thinning increase the intensity of risk factors such as root rot infection, bark beetle and storm damage in Norway spruce stands (Wallentin & Nilsson, 2013; Vollbrecht & Agestam, 1995; Stenlid, 1987). The intensity of spread of these risk factors is expected to increase under a future changing climate (Subramanian *et al.*, 2016a; Blennow *et al.*, 2010; Blennow *et al.*, 2006). Stand-level simulations using Heureka-DSS showed that adaptive strategies such as reducing rotation periods by avoiding thinning and switching to other tree species could reduce the intensity of risk factors like root rot infection, bark beetle damage and storm felling (Subramanian *et al.*, 2016a). Promoting shorter rotation periods by avoiding thinning in Norway spruce stands thus could reduce the spread of root rot infections, bark beetles, and storm damage. Moreover, this management approach was no less profitable than the conventional management practice for Norway spruce stands (Figure 9). Replacing Norway spruce with other species such as hybrid aspen and hybrid larch significantly increased expected profitability. Hybrid aspen and hybrid larch will be defoliated during winter, when storms are most frequent in Sweden. Therefore, stands of these species will be at a lower risk of storm damage than Norway spruce stands.

Landscape-level simulations using 3PG-Heureka showed that an adaptive management regime with shorter rotation periods and no thinning (the SR regime) provided effective protection against storm-felling in Kronoberg county. However, replacing Norway spruce with Scots pine (the PAS regime) was less effective (Figure 14).

5.5.1 Pros and cons of adaptation management regimes

Even though the Promoting alternative tree species (PAS) regime was less effective at protecting against storm-felling than the Shorter rotation length (SR) regime, it has been shown to reduce the spread of major pests and pathogens in Swedish forests such as root rot (*Heterobasidion parviporum*) and the spruce bark beetle (Piri & Valkonen, 2013) while also increasing the landscape's biodiversity. In addition to reducing the incidence of storm felling, the SR management regime also caused the annual net income from the forest to be more resilient towards major storm events than was the case for the

Business as usual + Storm (BAU+Storm) and PAS regimes (Figure 13). The major limitations of the SR regime are the risks associated with thinning-free management, such as an increased risk of natural mortality and snow damage (Štefančík, 2012; Rössler, 2006). The SR strategy also presents few selection opportunities and thus little scope to tune future wood quality, and prevents forest owners from deriving income via thinning at an early stage (Subramanian *et al.*, 2016a). Therefore, the financial benefits of a thinning-free approach such as the SR regime could be smaller than expected. Moreover, it would produce a landscape with dense stands of Norway spruce that could be less attractive for recreational purposes and would negatively affect the landscape's biodiversity.

6 Conclusions and future prospectus

Based on this work:

- The growth, biomass production and subsequent carbon sequestration capacity of Swedish forests will increase in future changing climate.
- The risk factors associated with future changing climate such as root rot infection, bark beetles damage, storm events could cause serious problems to growth and biomass production of Swedish forests.
- Even though environmental pollutants like tropospheric ozone could reduce the growth and carbon sequestration capacity of Swedish forests under changing climate their impact is minor when compared to risk factors such as root rot infection, bark beetle damage and storm events.
- Adaptation management measures such as avoiding thinning, reducing rotation length and switching to other exotic tree species such as hybrid aspen and hybrid larch could not only reduce the damages caused by risk factors associated with climate change but also economically profitable.
- The hybrid model 3PG-Heureka could be used for simulating forest variables in a broad spatial (stand to landscape) and temporal (from 5 years to more than 100 years) scale. However it should be improved to use it as a national level-planning tool for different stakeholders like forest industries, forest managers.
- This study was purely based on simulation models, therefore a lot of uncertainties are involved.
- There are lot of other factors, which might influence the growth and development of forests that are not considered in this this study. Therefore before formulating policy measures the possible uncertainty factors should be carefully addressed.

Climate change is one of the biggest challenges that our society is facing. It is also a major environmental issue that needs innovative thoughts, actions and most importantly serious collaborative efforts among different stakeholders involved. The need to quickly reduce global GHG emissions creates a major challenge to the way the energy is produced and consumed in society, creating a major opportunity for the forest sector to provide renewable energy and materials. Bio-economy strategies announced in the European Union create significant expectation for increased utilization of renewable and environment friendly bio-based alternatives such as bioenergy replacing fossil fuels and wood materials replacing oil-based plastics, concrete and steel (Hannerz *et al.*, 2014). This could only be achieved through a comprehensive system analysis approach; identifying suitable long-term carbon management measures thorough integrated management methods (Figure 1). An integrated management system that ensures steady flow of harvested wood in sufficient volume as raw material to forest based industries is essential in order to achieve the goals of EU bio-economy strategy. This can be achieved only in a landscape-level management system. The carbon balance in a forest stand switches dramatically from uptake to loss at final felling, whereas the carbon balance in a forest landscape fluctuates around the trend line that can be increasing decreasing or roughly stable (Lundmark *et al.*, 2014). Proper planning and timely implementation of management activities is the key factor that could help us to achieve EU bio-economy targets. Landscape-level simulation models such as 3PG-Heureka could effectively be utilized for long-term management planning under changing climatic conditions. Therefore more research works should be done in developing such models, which has the potential to be used as national-level planning tool. However we should not forget the famous saying "Essentially all models are wrong, but some are useful" (Box & Draper, 1987).

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