Evaluation of Process based Model 3-PG for Simulation of Net Primary Production of *Picea abies* in Northern and Southern Regions of Sweden under Climate Change

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Master thesis in forest management - Euroforester Master Program,
30 ECTS, Advanced level(AE2), SLU course code EX0630

Abstract

The results of this evaluation reveal good performance of 3-PG and seems reasonable to use it for simulation of net primary production in Sweden. Subsequently,the NPP of *Picea abies* was simulated using 3-PG for 110 years in northern and southern Sweden under climate change. RCA3 generated climate data on two emission scenarios (A2 and B2) was used in the simulations as driving variables. The initial stand data and site factors were taken from well known sites in northern and southern Sweden to determine fertility rating input factor of 3-PG and to use for input data for Heureka StandWise and 3-PG for simulation and validation. The outcome from the simulation of 2071-2100 in A2 and B2 scenario were summarized for 2071-75, 2076-80, 2081-85, 2086-90, 2091-95 & 2096-2100 and compared against their corresponding reference years (1961-1990). The average relative increment of NPP after 110 years was 89,7% and 60,5 % for A2 and B2 in northern and 88,6% & 60,3% for A2 & B2 of southern Sweden respectively. Higher relative increase of temperature in autumn, spring & winter in northern Sweden led to higher relative increase of NPP in northern than Southern Sweden in both scenarios. Sensitivity testing of the model based on predicted NPP was carried out independently for temperature, rainfall and fertility rating. The result pointed-out that NPP from 3-PG was more sensitive for fertility rating than for temperature and rainfall. Rainfall was almost indifferent for the test. Sensitivity of the factors considered in the exercise was found to be site dependent. Total biomass outputs from 3-PG and Heureka StandWise simulations were compared for validation. There was no significance difference between total biomass from the two models. Modeling efficiency was 78,5 % for northern and 89 % for southern Sweden. The average model bias explained the error with 8,6% and -3,2%; the mean absolute difference outcome was about 8,6% and 7% and the root mean square error was13% and 9,5% in northern & southern regions respectively. Overall, the results from this work suggest that there were possibilities to use 3-PG for predicting NPP in Sweden with due considerations of thinning operation, determination of fertility rating and Leaf area index outcomes.

Keywords: 3-PG model; Heureka StandWise; process based model; model evaluation; simulation; climate change; NPP; Norway spruce

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Abbreviations

3-PG - Physiological Principles in Predicting Growth
A.s.l. - Above Sea Level
AMB - Average model bias
APAR - Absorbed Photosynthetically Active Radiation
APARu - Absorbed Photosynthetically Active Radiation utilized
CO_2 - Carbon dioxide
DBH - Diameter at Breast Height
DM - Dry Mass
DSS - Decision Support System
ECHAM-A2 -Regional simulation made in A2- scenario with German ECHAM/OPYC3 General circulation model
ECHAM-B2- Regional simulation made in B2- scenario with German ECHAM/OPYC3 General circulation model
EF - Modeling Efficiency
GPP - Gross Primary Production
IPCC - Intergovernmental Panel on Climate Change
LAI - Leaf Area Index
LUE - Light Use Efficiency
MA%D - Mean Absolute Percent Difference
MAD - Mean Absolute Difference
MAI - Mean Annual Increment
mDBH - Mean Diameter at Breast Height
NPP - Net Primary Production
^{O}C - Degree Celsius
PBM - Process Based Model
PBMs - Process Based Models
P_n - Net Photosynthetic rate
ppm - Parts per million
PPt - Precipitation
R^2 - Coefficient of determination
RMSE- Root mean square error
SI - Site Index
SLA - Specific Leaf Area
SMHI- Swedish Meteorological and Hydrological Institute
SRES - Special Report on Emission Scenarios
Tmax - Monthly maximum temperature
Tmin - Monthly minimum temperature
VPD - Vapor Pressure Deficit
W_F - Dry Mass of foliage
W_R - Dry Mass of roots
W_S - Dry Mass of stem

1 Introduction

The growing agreement in acknowledging climate change, the need to understand & adapt to it , the change it enforces in forest management and the difficulty to predict NPP at large scale among others are driving the development and use of Process based models (PBMs) (Rodríguez-Suárez *et al.*, 2010; Sands, 2004; Sands, 2003; Matsushita & Tamura, 2002).

Though impacts of climate change will cause a comprehensive challenge on forest ecosystem its level depends on the adaptive & resilience capacity of the system(Adger *et al.*, 2007). Therefore, it calls for understanding the elements involved and needs an in-depth analysis of both systems for area specific & pertinent interventions (Parry *et al.*, 2007) to ensure sustainable forest production and management in particular. PBMs helps to understand & identify the type of management that could pave the way for exploiting an opportunity from the change and to avoid relevant risks (Linder, 2000).

On top of this, based on their degree of reliability & precision, process based growth model simulations assist to understand the ongoing physiological processes involved in growth and responses of tree species to the changing environment(Landsberg & Sands, 2010). More importantly helps to predict future scenarios in terms of growth & development as well as to pass an informed management decisions (Rötzer *et al.*, 2010; Sands, 2003; Bergh *et al.*, 1998) in a 'long- time persisting' systems of forestry production (Andersson *et al.*, 2005). Hence to determine the relative level of credibility of the model, its practical applicability & performance, and build consumers confidence and attitude towards the model; an ongoing evaluation process is needed (Pinjuv *et al.*, 2006; Vanclay & Skovsgaard, 1997).

Cognizant with this, PBMs allows for integration & simulation of biotic and abiotic interactions (Kissling *et al.*, 2011). Biotic & abiotic factors and their interaction plays significant role in forest production. These factors are essentially associated with climate variables (Lindner *et al.*, 2008). The climate system is complex and comprises of the land surface, snow & ice, ocean & other water bodies, living things and the atmosphere (IPCC, 2007a). The change in climate emanates from its own internal dynamics as well as from the change in volcanic eruption, solar variation, and physical & chemical composition of the atmosphere (IPCC, 2007a). These potential changes will have a possible effect on biotic and abiotic factors with a likely extended outcome on forest growth and development (Lindner *et al.*, 2008). Changes in climate variables like seasonal cycles of temperature coupled with irradiance and rainfall motivated by climate change alter phenology, seasonal growth pattern thereby bringing an impact on carbon balance, biomass production (Slaney *et al.*, 2007; Menzel *et al.*, 2006; Pussinen *et al.*, 2002; Bergh *et al.*, 1998) and length of rotation period(Pussinen *et al.*, 2002).

It is expected that forest production in northern Europe and boreal region could be favored by global warming (Bergh *et al.*, 2010; Pussinen *et al.*, 2009; Kirilenko & Sedjo, 2007). Climte change induced temperature increase in boreal region may extend growing season, favor decomposition & mineralization of nutrients and may make nitrogen readily available in due course affect forest tree production (Beedlow *et al.*, 2004; Norby *et al.*, 1999; Curtis, 1996). An extension of about two months of growing period in both autumn and spring is expected in Sweden (Bergh *et al.*, 2010 cited in Bergh *et al.*, 2010). Likewise, a change in the rate of photosynthesis due to enhanced carboxylation and direct fertilization both from raised level of carbon dioxide concentration will lead to an increased forest production (Beedlow *et al.*, 2004; Norby *et al.*, 1999; Curtis, 1996; McMurtrie & Wang, 1993).

In relation to this, results from several model based researches which have been done in boreal region support the above assumption and consistently agreed by indicating an increment of forest production in the face of climate change. Bergh *et al.,*(2010) underlined that the range of relative increase in net primary production (NPP) for the whole Sweden in three tree species at the end of this century might be 24% and 31% for B2 and A2 emission scenarios respectively. This has been also demonstrated by a number of authors such as(Pussinen *et al.*, 2009; Eggers *et al.*, 2008; Jansson *et al.*, 2008; Kirilenko & Sedjo, 2007; Briceño-Elizondo *et al.*, 2006; Karjalainen *et al.*, 2003).

Such an effort to understand the change in the physiological process of plants and simulation of production under climate change has practical advantage to users and the environment. This enables to create a way out by devising important adaptation and mitigation strategies in an attempt to ensure sustainable forest production and management. The issue is notably important for forest ecosystem as it demands long years to complete cycles of production (Albert & Schmidt, 2010). Thus maximum care should be taken on choices and application procedures of the model to reach such a conclusion and in recommending pertinent forest management practices.

Estimates of forest production under climate change using process based forest growth model 3-PG (physiological principles predicting growth) for the next 110 years are not common for the whole of Sweden. Thus this study attempted to make the forecast through evaluating performance of forest production when it is exposed to climate change. It is anticipated that NPP at the reference time and at the predicted scenario would be different because of climate change(Bergh *et al.*, 2010; Pussinen *et al.*, 2009).

This study focuses on the dynamic physiological process of tree growth and made simulation of NPP for Norway spruce in Sweden using 3-PG under A2 and B2 climate scenarios. Subsequently it also carried out evaluation (sensitivity and validation) of the growth model with the purpose of determining NPP. The validation was made by comparing the outcome of the simulated total biomass of 3-PG with the most common empirical model Heureka StandWise; and the sensitivity analysis of the model considered climate & site factors such as temperature, rain fall and fertility rating (FR). Specific objectives of the study include the following:

2 Objectives

- To simulate net primary production(NPP) of Norway spruce for A2 and B2 emission scenarios during 2071 to 2100 using the 3-PG model in northern & southern Sweden
- To compare simulated NPP (kg C/m^2/year) for A2 & B2 emission (2071-2100) scenarios with 'climate normal' periods of 1961-1990 in northern & southern regions of Sweden
- To conduct a sensitivity analysis of 3-PG output (NPP) to climatic & site factors like temperature, rainfall and fertility rating
- To validate the 3-PG model by comparing the simulated total biomass values of 3-PG with results from Heureka StandWise empirical model

3 Materials and Methods

Simulations of NPP under different climate scenarios, calibration, sensitivity analysis and validation in this thesis are based on 3PGpjs version 2.7 (Sands, 2010).

3.1 Study area

This evaluation and simulation study was done in northern and southern regions of Sweden. The total numbers of Counties considered in this study were stepped up from 21 to 24 due to splitting up of larger counties, in northern Sweden like Norbotten, Västerbotten and Jämtland, in to two. The split was to obtain actual climate data from more observation points. Meteorological data were taken from each county. Whereas, site factor and stand initialization data were obtained from four representative sites corresponding to each region (Flakaliden & Bräcke in north and Asa & Ljungbyhed in south). Data from Bräcke & Ljungbyhed were used for determination of FR and information from other sites was for model validation & simulation of NPP. Northern Sweden comprised of 8 counties and southern 16 counties.

In Sweden, as one moves from southern to northern region the growing period, precipitation, amount of radiation, site productivity decreases and gets colder & snow cover increases (Kleja *et al.*, 2008; Bergh *et al.*, 1999; Morén & Perttu, 1994). The average annual productivity in Sweden is 5.3 m^3/ ha (Nilsson & Wastenson, 1990). This figure varies across different parts of Sweden. In southern it varies between 8.7 m^3/ ha & 11.5 m^3/ ha; the corresponding figure for north drop to 3 m^3/ ha (Nilsson & Wastenson, 1990). Most Swedish forests in northern Sweden is a part of the boreal vegetation zone, while a very large part of southern belongs to boreo-nemoral (Ekelund et al., 2000). Norway spruce is the dominant tree species in southern and Scots pine in northern (Loman, 2011). Though their abundance is low, there are also other important forest tree species(Loman, 2011). Specific illustrations about each region & corresponding sites are described below.

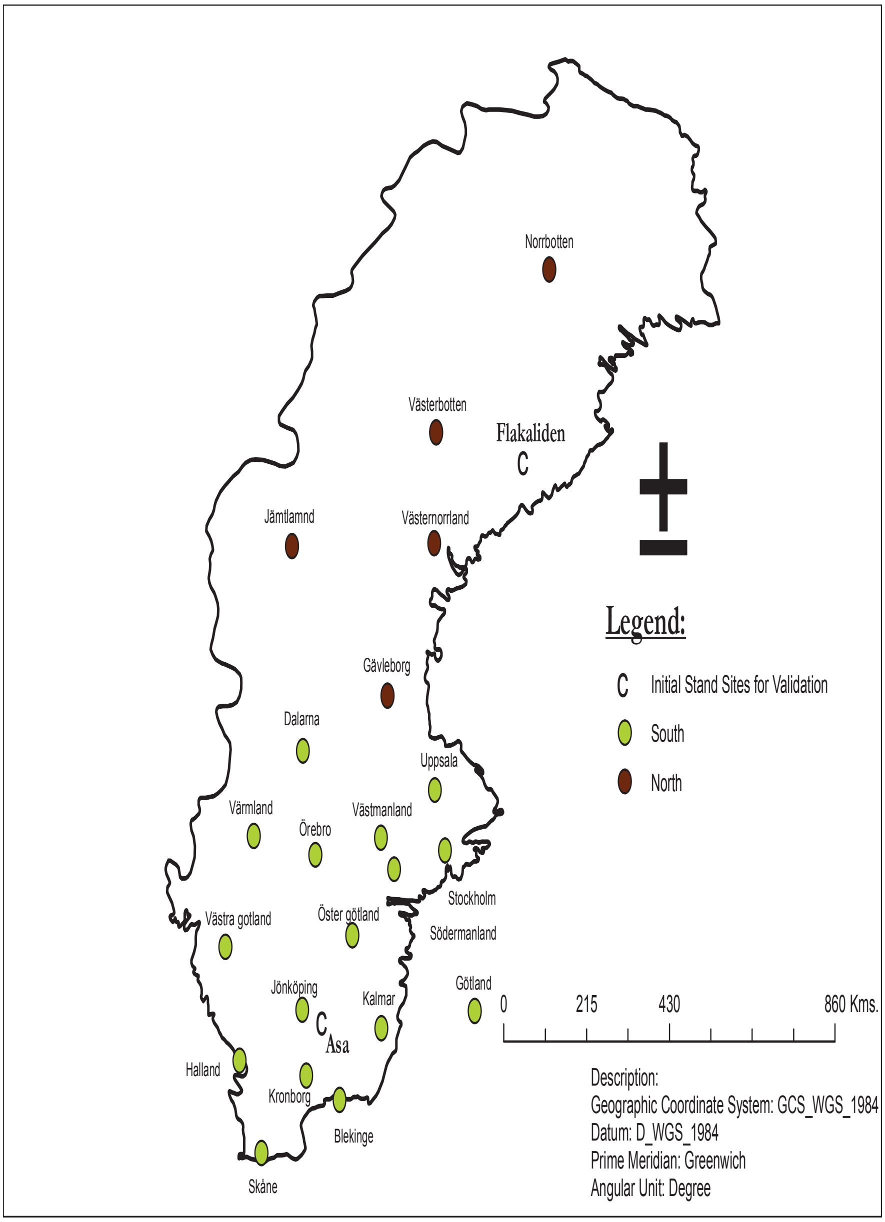

Figure 1: Map of the study area

3.1.1 North Region

Northern region of Sweden is affected and characterized by a boreal climate(Ekelund *et al.*, 2000; Bergh *et al.*, 1999).The climate is harsh with short growing season (100-160 days) with poor soils and low site productivity (Wallentin, 2007). Nitrogen is mainly limiting nutrient while water is normally sufficient and does not limit growth of trees (Bergh et al., 2005).

Bräcke from Jamtland was chosen for calibration. It is positioned 62^0 43N & $15^0$51E (Bergh *et al.*, 2008). Flakaliden situated in Västerbottens county represent areas in northern region and used to define site condition and stand initialization for validation of the model. It is located $64^0$07N and $19^0$27E. Its altitude is about 310m above sea level (a.s.l.) (Linder, 1990). Monthly mean temperature ranges between -8.7 °C (February) and 14.4 °C (July).The mean temperature during the growing season is about 10.2 °C and has 120 days growing period. Mid October to mid May is time for snow cover (Bergh *et al.*, 2005; Bergh *et al.*, 1998). Mean annual precipitation is about 600 mm. Growth is not restricted due to moisture whereas nutrient status of the soil is poor with site index (SI) of about G20 for Norway spruce. The soil is sandy, thin, podozolic and glacial till. (Bergh *et al.*, 2005; Bergh *et al.*, 1998).

3.1.2 South Region

Southern Sweden has soils with higher nutrient availability compared with northern Sweden, which enhance tree growth and development (Bergh *et al.*, 2010; Wallentin, 2007). The challenge of production in this part of the country is shortage of moisture (Bergh *et al.*, 2010). On the other hand, it has relatively longer growing period(Bergh *et al.*, 1999). In relation to this, Ekelund *et al.,* (2000) pointed out that the growing period in south begins at about two months prior to the north parts of the country.

Ljunbyhed from Skåne was chosen for calibration. It is positioned 56^0 05□N & $13^0$04□E (Svensson, 2006). Asa located in Jonkoping County is a representative site for validation in this region. It lies between 57^o08´N and $14^0$45´E. The mean annual precipitation, mean temperature and growing days are about 700 mm & 190 respectively (Bergh *et al.*, 2005). The annual mean temperature reaches around 11.5 ^{0}C during the growing season and has an altitude ranging from 225 to 250m a.s.l. (Bergh *et al.*, 2005). The soil is grouped under sandy-silt and the SI for Norway spruce ranges between 20 & 36 (Blennow *et al.*, 2010).

3.2 3-PG and its Major Components

3-PG was developed by Landsberg and Waring in 1997. It is dynamic & largely used growth model with flexible, transparent as well as simple structure to estimate growth on even aged stands (Landsberg & Sands, 2010; Rodríguez-Suárez *et al.*, 2010; Sands, 2010; Almeida *et al.*, 2004a; Almeida *et al.*, 2004b; Esprey *et al.*, 2004; Sands, 2004; Sands & Landsberg, 2002). Besides, it can potentially handle tree species grown in a monoculture in a wide range of geographical location, and also can be applied to mixed stands if average values for allometric relations are available, although species specific parameters are needed (Waring *et al.*, 2008; Coops *et al.*, 1998).

3-PG is between process and measurement based models. Inputs of monthly data were suggested for use to run simulation. The outputs could be either annually or monthly depending on the intended purpose of the simulation (Landsberg & Sands, 2010; Sands, 2010). Diagrammatic explanations about the model are shown below.

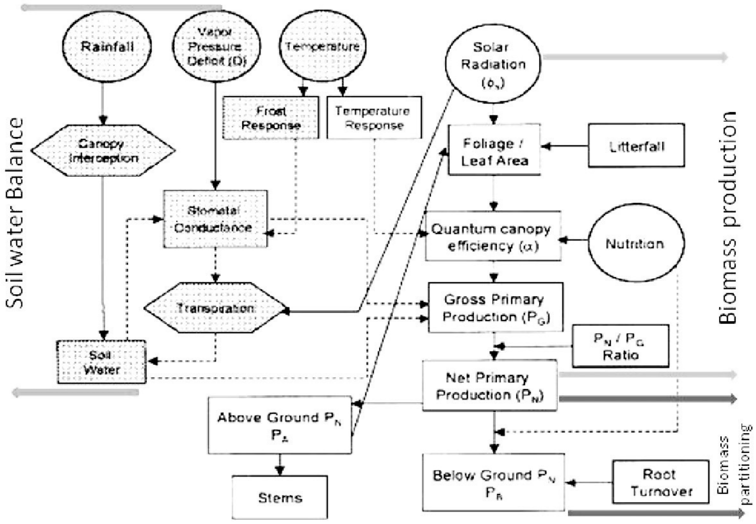

Figure 2: Schematic representation of the 3-PG model
Source: Tickle et al., (2001)

3.2.1 Basic Equations of 3-PG

McMurtrie & Wolf, (1983) illustrations were the foundation for 3-PG carbon balance equation. It is assumed that the value of 'X' changes over time't' days and designated as 'x' then

$\Delta W_R = n_R P_n - \gamma_R W_R \Delta t - m_R (W_R/N)\, \Delta N)$ (1)

$\Delta W_S = n_S P_n - m_S\, (W_S/N)\, \Delta N)$ (2)

$\Delta W_F = n_F P_n - \gamma_F W_F \Delta t - m_F\, (W_F/N)\, \Delta N)$ (3)

Where P_n= NPP which is expressed in ton/ha/day, n_i= fraction of NPP allocated to the i^{th} pool, γ_F= litter fall rate per day, m_i = fraction of biomass per tree lost in the i^{th} pool when a tree dies, γ_R = root turnover rate per day, N= Number of stems per ha,W_R= dry mass of root, W_S= dry mass of stem, W_F= dry mass of foliage (Sands, 2004).

3.2.2 Model interface

The excel based interface built for running 3-PG previously 3-PGpjs (now 3-PGXL) is user friendly and allows to undertake single site, multiple site, site-series and sensitivity analysis run. The process of the run assists to simulate production and undertake sensitivity of stand development (Sands, 2010). A useful attribute of the interface which allows parameters and site factors to be age dependent enable to simulate silvicultural events and to look for changes on the output variables. This changes are mainly as the result of input changes related to site conditions (Sands, 2010). The model interface is flexible enough to accommodate changes in site factors and default parameters (Sands, 2010)

3.2.3 Basic Elements of 3-PG

Major components of 3PG mainly deal with biology and physiology of growth. It also extends its procedure to include a conversion module(Landsberg & Sands, 2010).

Biomass production and determination of NPP

Gross Primary production (GPP) is proportional to intercepted photosynthetically active radiation (PAR). Canopy quantum efficiency with absorbed photosynthetically active radiation utilized (APARu) was used to estimate the GPP of the tree. Absorbed photosynthetically active radiation (APAR) was an ultimate source for APARu. Considering incoming solar radiation and leaf area, Beer's law facilitated to determine the net solar radiation intercepted and used (Sands, 2004).

Light use efficiency (LUE), which is the main philosophy in this model, was used as an approach for predicting growth and to determine NPP. Input data for the model like site & environmental factors affect LUE, canopy quantum efficiency, canopy conductance and help in estimation of APARu. This effect was reflected through growth modifiers and involved in the model with values between 0 and 1 (Landsberg & Sands, 2010; Sands, 2004; Coops *et al.*, 1998).

The model used established constant carbon efficiency to get the NPP (Landsberg & Sands, 2010; Almeida *et al.*, 2004a; Waring *et al.*, 1998). Thus the net biomass was the result of constant fraction of GPP. This debatable fraction (Landsberg & Sands, 2010; Tome, 2004) was assumed as constant (0.47± 0.04 of GPP) for various tree species under different geographical settings (Waring *et al.*, 1998). Leaf area index and soil water balance for estimation of biomass production were from biomass partitioning and soil water sub models respectively (Landsberg & Sands, 2010). The primary output in this sub model was NPP and loss through respiration (Sands, 2004). Assimilate produced from this sub model served as an input for the next sub module(Landsberg & Sands, 2010).

Biomass partitioning

This is a process of distributing carbon to above & below ground pools. Pattern of growth is influenced through this process (Landsberg & Sands, 2010).The impacts of litter fall and root turnover was taken in to consideration as they were responsible for losses. Stem (bark and branch) & foliage and roots belong to above and below ground allocation sites respectively (Sands & Landsberg, 2002; Landsberg & Waring, 1997).

Partitioning to different plant parts depend on plant soil water, fertility (environmental factors) and stem diameter. Availability of soil water and nutrients in optimum will favor above ground growth, on the other hand stress of these factors enhance partitioning to roots. High diameter at breast height (DBH) facilitate more allocation of assimilate to stem than foliage (Esprey *et al.*, 2004; Sands & Landsberg, 2002; Landsberg & Waring, 1997).

Allometric relationships between attributes of trees like leaf and stem mass were employed to anticipate the ratio of biomass distributed to foliage and stem (Landsberg & Sands, 2010; Almeida *et al.*, 2004a; Dye *et al.*, 2004). Litter fall and root turn over coupled with biomass pools and canopy Leaf area index (LAI) values were considered as primary output of the sub-model (Sands & Landsberg, 2002; Landsberg & Waring, 1997).

Stem numbers and Mortality

The dynamics of stem numbers with in a stand was one more important factor while dealing with modeling and carbon sequestration. It followed a constant or age dependent probability of death with self thinning rule (Landsberg & Sands, 2010; Sands, 2004). Self thinning follows the -3/2 power /self-thinning rule. This law assists in dealing with arithmetic's of stem number (Nambiar & Ferguson, 2005; Drew & Flewelling, 1977).

Self thinning and other stress related factors inducing mortality depend on basal area and age of the stand respectively. Stem mass from biomass partitioning sub module facilitated determination of basal area. Competitions of resources subsequent to canopy closure facilitate self thinning (Landsberg & Sands, 2010; Sands, 2004). Number of stems per unit area was a primary output for this sub model. In stands dominated with single species dynamics of stem numbers can be better explained and envisaged (Landsberg & Sands, 2010).

Soil water balance

This sub model in 3-PG operates in a single soil layer. The primary source of moisture is rainfall and irrigation. Canopy interception (which is assumed as fixed percent of rainfall and proportional to canopy LAI), evapotranspiration and drainage (runoff) are responsible for loss of water(Landsberg & Sands, 2010; Sands, 2004). LAI and stomatal conductance have an influential role on canopy conductance. Interception loss and canopy conductance increases with increasing canopy LAI. Leaf area index, vapor pressure deficit (VPD), solar radiation and soil water affects the process of evapotranspiration which indirectly have an influence to loss or maintenance of moisture. The outcome for this sub model is soil water content (Landsberg & Sands, 2010; Sands, 2004).

Module conversion

This module yields an output data like stem volume, mean annual increment (MAI) etc to satisfy demands of forest managers. The input for this module was the biological output from biomass pools notably stem biomass (Landsberg & Sands, 2010; Sands, 2004).

3.2.4 Model input data

The input data for the model includes of weather data, site factor, stand initialization and species focused parameters(Landsberg & Sands, 2010).

Climate data

The important climate data to embark the simulation include monthly minimum & maximum temperature, amount of rainfall, frost & rain days, and solar radiation. Other inputs like VPD and solar insolation can be derived from the available weather data (maximum and minimum temperature) using the weather module. Average monthly data can be fixed using the daily observation. The rainfall days and amount can be counted & summed respectively (Landsberg & Sands, 2010).

Unless there are specific needs to work on particular events like drought 3PG uses long-term average data for simulation (Landsberg *et al.*, 2003; Landsberg *et al.*, 2001). These attributes was one more factor that makes the model fit to analyze situations with in a changing environment (Esprey *et al.*, 2004).

The Swedish Metrological and Hydrological Institute web site (www.smhi.se) was served as a source to climate input data. While downloading climate data an effort was being made to include as much as observation points in a county in order to increase representation of sites. Data from observation points were averaged and combined to make County based monthly data. Climate data were recorded from January 1961 to December 1990 and January 2071 to December 2100 for climate normal and climate change scenario respectively. Units of climate parameters like temperature, solar radiation and rainfall from the regional climate model have been converted in to units that are compatible to 3-PG. Finally the average climate variable data from each county by month was aggregated in to regions (northern and southern Sweden) for simulation.

Site factor

Site factors commonly used was soil class, latitude, soil water content and soil fertility. The available soil water content was from soil texture, soil depth and water holding capacity (Landsberg & Sands, 2010). Soil fertility value is mostly fixed based on expert knowledge of the specific site and rated with values from zero to one. This rating was attached to fertility due to the difficulty to describe fertility status of sites efficiently. 0 values are for sites where there is growth limitation because of fertility and 1 is for areas with no fertility problems (Landsberg & Sands, 2010). FR was determined based on simulation of 3-PG until a best fit was obtained with Heureka StandWise simulation using input data from Bräcke and Ljungbyhed for both models. The fertility rating value used in the reference scenario was not subjected to change while placed in use for running future climate. Though this value was expected to be modified by climate change, there are, however, no mechanisms of knowing how FR might change with climate and there is no value determined for this specific purpose (Peter Sands, personal communication, June 6 th, 2012). Site factors other than FR for validation were from Asa for southern and Flakaliden for northern Sweden for two of the models.

Stand initialization

There is no specific age for the initial stand to start the simulation and can be done at any point in time for many years depending on the interests of the user(Landsberg & Sands, 2010). Initial data for the stand must be estimated for Stock densities, initial biomass accumulated on root, stem & foliage and soil water content. Empirical relations, observation and consideration of standard seedling during planting are the methods to be employed to estimate the initial biomass (Landsberg & Sands, 2010).

Stocking of 2000 /ha was used as an initial data. Simulation for the purpose of this work started at the age of 42 and 26 when the stand attains a height of 9m in northern and southern Sweden respectively. The output data like foliage, stem and root dry mass from Heureka StandWise was used as an input initial stand data for 3-PG run. Thinning grade, intensity and timing was scheduled using the guideline for each region and thinning form used was from below while simulating Heureka. Defoliation rate of 20% was used in this exercise which is considered as normal in Sweden (Loman, 2011). As the foregoing paragraph silvicultural events like thinning (proportion of biomass of foliage, stem & roots removed) and defoliation (% of leaves that will remain) in 3-PG was determined from various pertinent out puts of Heureka-StandWise simulation.

Table 1 Thinning Program of each region as represented from Asa & Flakalideen. The intensity was calculated using basal area difference before and after thinning from Heureka standwise simulation.

Regions	Initial stocking	Thinning at age	Grade %
North	2000	57	32
		72	35
		87	35
South	2000	36	30
		46	32

Species specific parameters

These are parameters to describe the species and are specific to it. Species parameter values can be obtained based on experimental data using statistical analysis, direct measurement, using values of other tree species and indirect measurement by trial and error to make output values fit with observed data (Landsberg & Sands, 2010; Sands, 2004). This study used a species specific parameter values of *Picea abies* in Sweden for 3-PG which was obtained from the work done by (Subramanian, 2010).These parameter values can be found in appendix.

3.2.5 Model output

Stand evapotranspiration, NPP, specific leaf area, canopy leaf area index, biomass pools (WF,WR,WS), number of stems, plant available moisture, basal area, mean stem volume, MAI and mDBH (mean diameter at breast height) are simulation outputs of the model (Sands, 2004). DBH, basal area, and stem number are from biological sub- models of 3-PG.whereas, dominant height, MAI, stem volume can be computed from these variables(Landsberg & Sands, 2010).

3.3 Heureka growth model

Heureka is an empirical growth model to forecast forest development, for inventory purpose, evaluation and data preparation all providing significant role in supporting decision. Besides, simulations of Heureka enable to determine carbon sequestration, recreation services of a forest and suitability of habitat. The Heureka Forestry Decision support System (DSS) was developed by Swedish Agricultural University (Wikström *et al.*, 2011; SLU, 2010). It can be applied at RegWise (regional analysis), StandWise (stand analysis) and PlanWise (consider individual holding) level depending on specific interests. These are the central theme of the software package. In addition to this, there are subsidiary & supportive modules such as PlanStart, Ivent and PlanEval for importing data, making field inventory and to pass an informed decision based on alternative management plan comparisons respectively (Wikström *et al.*, 2011; SLU, 2010).

In Heureka, stand with desired attributes was established by considering typical representative SI of specific area for Norway spruce. This can be further used to determine the age and basal area at 9 m dominant height of the stand. In this case the typical SI for Norway spruce used while initiating the run was G22 and G30 for northern & southern Sweden respectively. The age and basal area estimation processes were carried out with the help of an excel function called Div funktioner (Urban Nilsson, Personal communication, June 13 th, 2012). The value of stand height and number of stems enabled to establish stand basal area. Based on these and other input data such as altitude, latitude, soil moisture, soil fertility and vegetation type a pre-simulation can be started until best fit for the typical SI is found. Determination of an exact or a very near value to the typical SI declares the establishment of an ideal stand which was ready to commence prediction of growth for the desired tree species. It used 5 years of time scale as a period to generate its outputs. Biomass for bark, branch, needles, roots & stems, basal area, standing volume, dominant height and volume harvested were among the outputs from Heureka-StandWise simulation (Elfving & Nyström, 2010).

3.4 Climate change and its scenarios

Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) described the emission scenarios with different storyline and scenario family. There are various categories depicted in the report with different assumption in future development (Nakicenovic *et al.*, 2000). Among all regional scenarios A2 & B2 were considered for simulation of climate change and climate normal scenarios in this study.

B2 consider a world enjoying economic and population development of medium level. Technological development is less rapid and diverse but still better than A2. Whereas, in A2 it is assumed that there will be gradual advancement both in technology & economic development which is lower than B2. It is however expected a rise in population higher than B2. Due to an increase in population forest area will decrease in this scenario (IPCC, 2007b; Nakicenovic *et al.*, 2000). In general the position of the drivers tend to enhance emission level in A2 than B2 (Solomon *et al.*, 2007; Nakicenovic & Swart, 2000).

In this study the A2 emission scenario for climate normal used mean value of carbon dioxide (CO2) concentration of 350 parts per million (ppm). The corresponding number for A2 and B2 of the changing climate scenario was 572 and 726 ppm respectively by the year 2085. The mean global warming was 2.3^{O}C for B2 and 3.2 ^{O}C for A2. It was also noticed that there was smaller and higher increase of temperature during summer and winter seasons of the year respectively (Nakicenovic & Swart, 2000). Corresponding to this general IPCC global and previous continent & country level predictions, regional models anticipated a mean annual temperature increase in Sweden of 3.6 ^{O}C to 4.5 ^{O}C in the A2 and 2.5 to 3.5 in the B2, respectively, while precipitation ranged from 12 to 23% and 8 % to 17 % for A2 and B2 scenarios respectively(Koca *et al.*, 2006).

A more detailed and with high resolution Rossby centre's regional atmosphere model RCA3 from ENSEMBLES project was used for generation of climate data. The model was used for 1961-2100 climate change projection and regard observed greenhouse gas concentration and IPCC SRES 2000 data for 1961-1990 and 1991-2100 respectively(Kjellström *et al.*, 2005).

The boundary conditions for this regional climate model were downscaled from atmospheric general circulation global based climate model i.e. ECHAM4 developed by the Max Plank Institute. This has a paramount importance to make the resolution fine & produce better representations of vegetation, topography and distribution of land surface & water bodies. In ECHAM4 there was a possibility of finding scenario results in A2 and B2 forms. RCA3 model used horizontal spatial high-resolution of about 50 x 50 km and monthly time resolution (Kjellström *et al.*, 2005).

3.5 Analysis of climate data

The major climatic driving variables considered in this simulation study were temperature and rainfall. The climate data was divided in to five years and grouped in to six time series compartments. The analysis considered the data which were grouped in to five years and when necessary dealt with the whole projection period and season based scenarios. This was done to get higher resolution to see how the climate scenario and prediction of NPP developed over time. Average temperature is the mean value of Tmax & Tmin. The difference between average temperature in climate normal and climate change scenario for each time period is the relative change.

3.5.1 Temperature

The monthly average temperature both for A2 & B2 scenarios for 2071-2100 has shown a positive increment from its reference scenarios in north and south regions. The relative average increment through the projection time was 4,5 for A2 and 3,6 ^{O}C for B2 in northern and 4,5 ^{O}C for A2 and 3,4 ^{O}C for B2 in southern Sweden. Though the average temperature percent change appears almost similar in value the relative progress was higher in northern than southern Sweden in autumn, spring and winter (Table 2 and 3).

Table 2 Relative average temperature increments in ^{O}C through the whole projection, five years breakdown time scale and seasons of the climate change scenario of A2 & B2 in northern Sweden.

Season	2071-75		2076-80		2081-85		2086-90		2091-95		2096-100		Season Mean	
	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2
Autumn	4,4	2,8	3,5	3,0	5,1	3,8	4,2	3,3	3,7	2,9	5,2	3,8	4,3	3,3
winter	6,4	3,4	6,1	5,5	5,6	5,6	7,1	6,0	4,0	1,9	6,5	5,3	6,0	4,7
Spring	4,2	2,3	5,0	4,2	5,2	3,8	6,4	4,3	4,0	3,6	4,8	4,9	4,9	3,9
Summer	2,8	2,1	2,6	1,9	2,6	1,2	3,4	2,8	1,7	1,8	3,8	3,3	2,8	2,2
Mean	4,5	2,7	4,3	3,6	4,6	3,6	5,3	4,1	3,4	2,6	5,1	4,4	4,5	3,6

Similarly the seasonal variation of predicted temperature increment for the whole projection period (thirty years) showed highest temperature in winter and lowest in summer in both scenarios and regions. The increment in A2 was greater than B2 as well (Table 2 and 3). On the other hand, in a five years time scale breakdown the trend of relative average temperature increment within each series of time varied and showed higher reduction in 2091-2095 both in A2 and B2 scenarios in south and north regions. A slight decline was also recorded for A2 scenario in northern Sweden for 2076-2080 periods (Table 2 and 3).

Table 3 Relative average temperature increments in ^{O}C through the whole projection, five years breakdown time scale & seasons of the climate change scenario of A2 & B2 in southern Sweden.

Season	2071-75		2076-80		2081-85		2086-90		2091-95		2096-100		Season mean	
	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2
Autumn	4,0	2,7	3,3	2,7	5,0	3,9	4,2	3,3	3,2	2,5	5,1	4,1	4,1	3,2
winter	4,6	2,3	5,4	5,1	3,8	4,6	6,8	5,8	4,7	2,1	6,4	5,4	5,3	4,2
Spring	3,8	2,6	5,1	4,1	5,0	3,4	5,7	4,1	4,1	2,9	4,7	4,4	4,7	3,6
Summer	3,5	2,8	3,6	3,0	3,6	2,0	3,6	2,8	2,8	2,6	5,1	3,4	3,7	2,8
Mean	4,0	2,6	4,3	3,7	4,3	3,5	5,1	4,0	3,7	2,5	5,3	4,3	4,5	3,4

3.5.2 Rain fall

Prediction of rainfall demonstrated both an increase and decrease from the reference climate in both regions and scenarios. Across the comparisons made between the predicted change and reference scenario more months was frequently noticed with rain fall value less than zero in southern than northern Sweden. The trend showed relative average increment of 9, 8 mm in A2 and 10,4mm in B2 in south and 20,7mm in A2 and 15,3mm in B2 for north (Table 4).

Generally lower values of rainfall from the reference scenarios were recorded in southern region from April to September where it was more pronounced from July to August in both A2 and B2 scenarios. Reduction of rainfall values occurred in north from May to September. Specifically B2 scenario of southern Sweden was higher from A2 mainly in the months of February, July and September. The corresponding months for northern Sweden was June, September and November.

Table 4 Season based relative average rainfall increment in mm through the whole projection time

Region	Scenario	Season based average rainfall increment				Mean
		Winter	Spring	Summer	Autumn	
North	A2	31,3	20,8	5,3	25,1	20,7
	B2	24,0	12,3	1,9	23,0	15,3
South	A2	29,2	12,2	-20,7	18,4	9,8
	B2	25,2	8,6	-7,0	14,8	10,4

The trend for season based relative increment showed positive values. The increment was highest in winter and lowest in summer in both scenarios and regions. The magnitude of the increment in A2 was also high during winter when compared with B2 (Table 4).

3.6 Simulations

A number of simulations, with 3-PG and Heureka StandWise, were made in order to predict NPP, determine values of FR, anticipating total biomass for validation and for sensitivity analysis. In the sensitivity analysis, values of temperature, rain fall and FR was modified in climate normal and climate change years, scenarios and regions. Simulations of Huereka-StandWise were to get value of total biomass for determination of FR and validation of 3-PG and to avail part of the initial stand data for 3-PG.

The model simulations used 1961 as a starting year for the reference climate which was a reference run, while 2071 was assumed as initial year of climate change impacted simulations under A2 and B2 emission scenarios. Potential NPP of reference run was compared with the simulation result under climate change of both scenarios and between northern and southern regions to get the relative change. The unit of NPP was converted in to kg C/m^2 /year from its default units of tonnes dry mass/ha/year. In most cases five years average were used for comparison but sometimes average values for the whole simulation period were also used.

3.7 Evaluation

Model evaluation includes verification, validation, calibration and sensitivity analysis (Rykiel, 1996). In this study sensitivity analysis and validation were conducted. Calibration was done only to fix value of FR for 3-PG.

3.7.1 Sensitivity analysis

Sensitivity analysis is a process of injecting change on values of input variables to assess the effect that the change will have on the model's output (Esprey *et al.*, 2004; Vanclay & Skovsgaard, 1997). The behaviors of the model and parameter values are with significant importance while thinking of sensitivity (Sands & Landsberg, 2002).

Sensitivity of 3-PG output (NPP) was tested against temperature, rainfall and fertility rating. These inputs were selected based on their determinant role on corresponding result of NPP prediction (Esprey *et al.*, 2004; Esprey & Smith, 2002).

The relative sensitivity was carried out using a simple comparison between NPP of 3-PG under climate normal, climate change years and NPP value after the change of specific inputs of the corresponding time in both regions. Except for the variable considered for the test other input variables remains the same with their corresponding value of the climate normal and climate change years. This has created a paramount importance to examine the effect of temperature, rain fall and fertility rating variations in each run (Landsberg & Sands, 2010). The sensitivity analysis considers an increase of ±30% in temperature & rainfall from 1961-1990 and 2071-2100 (Esprey *et al.*, 2004; Battaglia & Sands, 1998). These modifications were applied uniformly to monthly values of maximum & minimum temperature and rainfall. Fertility rating was allocated with ± 0,2 (±20%) from previously determined fertility rating value(Battaglia & Sands, 1998).

The model was run separately for these changing circumstances to determine the NPP and facilitate the comparison. It is expected that the relative sensitivity of NPP to the input data would be negative, zero or positive based on the subsequent effect of inputs (Landsberg & Sands, 2010). The arithmetic calculation of sensitivity of 3-PG for the changing inputs was done using the following formula.

Relative change (%) in NPP= ((NPP after ±30% perturbation in temperature and rain fall value from each base years) - (NPP from 1961-90 & 2071-2100 A2 & B2))/NPP from 1961-90 & 2071-2100 A2 & B2 in % (4)

The same arithmetic procedure applied for sensitivity of FR save the change in value. Temperature and rainfall data for the sensitivity analysis was taken from 8 sites in northern and 16 sites (counties) in southern Sweden.

3.7.2 Model validation

Validation deals with checking of accuracy and consistency (Jorgensen, 1986). An outcome from Heureka-StandWise simulation was used for comparison and initiating the validation exercise in places of observation values. This was due to the fact that empirical models reveal results of better accuracy than PBMs (Vanclay, 1994). This validation exercise was not accomplished in a comprehensive way; it was, however, designed for the purpose of simulating NPP.

The evaluation was performed for total biomass because of unavailability of output variable in the form of NPP in Heureka StandWise. Though there would be slight interdependency of total biomass in a time scale, it could better explain the process than biomass increment and other forms of parameters as the objective was to look on the scenario of forest development and to predict the general trend of NPP through the whole rotation. More to the point, it is also common to use biomass data to estimate NPP at a local scale (Field *et al.*, 1995).

The comparison was undertaken by using average of five years total biomass from 3-PG. This was to create compatibility with outputs of Heureka-StandWise, which have output with five years time scale resolution. The unit of measurement for biomass in both models are tonnes DM/ha.

Correlation and error was characterized using various analyses. Outcomes from 3-PG were subjected to coefficient of determination (R^2). However, it was not tempting to rely on R^2 for validation as it merely asses the linear relationship between variables, sensitive to outliers, insensitive for differences between observed and predicted values (Legates & McCabe Jr, 1999). Thus to bridge up this gap statistical error index (MAD, average model bias (AMB), RMSE) and model evaluation statistics (modeling efficiency (EF)) were supplemented (Legates & McCabe Jr, 1999). Besides, t-test was employed to look on their difference in prediction (Härkönen *et al.*, 2010). These combinations of statistical tests were believed to allow for investigating the process within the model as there is no single criterion to discharge comprehensive aspects of model validation (Vanclay & Skovsgaard, 1997).

3.8 Statistical analysis

A simple measure of central tendency like mean and measure of statistical dispersion or reliability of simulation such as regression, AMB, MAD, RMSE and EF were undertaken. The formula used for each measures are depicted below.

$$MAD = \left(\frac{\sum |yi - \hat{y}i|}{N}\right) \quad (5)$$

$$AMB = \left(\frac{\sum (yi - \hat{y}i)}{N} \right) \tag{6}$$

$$MA\%D = \frac{100[\sum(|yi - \hat{y}i|/|yi|)]}{N} \tag{7}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(yi - \hat{y}i)^2}{N}} \tag{8}$$

$$EF = 1 - \left(\frac{\sum_{(yi - \hat{y}i)}2}{\sum_{(yi - \bar{y}i)}2} \right) \tag{9}$$

Where y_i is the value from Heuereka which is considered as observed, $\hat{y}_i$ is the simulated value from 3-PG, $\bar{y}$ is the average of the Heureka value and N is the total number of total biomass observations from the models. Significance of the bias was analyzed by means of paired t-test for dependent samples(Härkönen *et al.*, 2010). P-value $<$ 0.05 was assumed to be significant. The mean of the observation is the denominator for the value of RMSE to find RMSE in %(Härkönen *et al.*, 2010).

4 Results

4.1 Prediction of net primary production

The results from the simulation indicate an increase of NPP for A2 and B2 scenarios relative to the corresponding reference run in both regions of Sweden. A model estimate of NPP in B2 is lower than A2 in the two regions as well. The average relative increment of mean total NPP after 110 years of time is 89,7% and 60,5 % for A2 and B2 in northern and 88,6% & 60,3% for A2 and B2 of southern Sweden. The range of NPP in the reference scenario lies between 0, 39 to 0, 49 Kg C/ m^2/ year in northern and 0,82 to 0,87 kg C/m^2/year for southern Sweden (Table 5 and 6).

Table 5 Comparison of relative change in mean total NPP between climate normal and climate change scenarios in % for northern Sweden. NPP is in kg C/m^2/yr

Stand age	Reference years	NPP	Climate change years	NPP		Relative change of NPP in %	
				A2	B2	A2	B2
42-46	1961-65	0,49	2071-75	0,84	0,69	71,4	40,8
47-51	1966-70	0,48	2076-80	0,87	0,74	81,2	54,1
52-56	1971-75	0,48	2081-85	0,90	0,71	87,5	47,9
57-61	1976-80	0,45	2086-90	0,85	0,73	88,9	62,2
62-66	1981-85	0,44	2091-95	0,83	0,74	88,6	68,1
67-71	1986-90	0,39	2096-2100	0,86	0,74	120,5	89,7
Mean		0,46		0,86	0,73	89,7	60,5

The relative increase of NPP in northern Sweden is higher than southern in A2 and B2 scenarios both in average values for the whole period and variation between periods. Breaking the whole simulation in to five years step periods, the trend of relative growth in NPP started with lower values in northern compared with southern Sweden. Through time the raise between periods becomes larger and ends up with higher relative increase in northern than southern Sweden. The value lies between 71,4% to 120,5 % in A2 and 40,8 % to 89,7% in B2 for northern Sweden and 83,1% to 96,8% in A2 & 57,3 % to 68,5% in B2 for southern (Table 5 &6).

The data in table 5 and 6 suggest that the highest relative increment of NPP is obtained during the last time steps (2096-2100) in both scenarios and regions. In a similar way the lowest is attained during the first time step (2071-75) in northern Sweden in A2 and B2 scenarios. For southern Sweden this happened during 2086-90 for A2 and 2081-85 in B2 scenario.

Table 6 Comparison of relative change in mean total NPP between climate normal and climate change scenarios in % in southern Sweden. NPP is in kg C/m^2/yr

Stand age	Reference years	NPP	Climate change years	NPP		Relative change of NPP in %	
				A2	B2	A2	B2
26-30	1961-65	0,82	2071-75	1,53	1,30	86,1	58,1
31-35	1966-70	0,86	2076-80	1,59	1,37	85,6	59,1
36-40	1971-75	0,86	2081-85	1,65	1,35	92,0	57,3
41-46	1976-80	0,87	2086-90	1,59	1,37	83,1	57,9
46-50	1981-85	0,84	2091-95	1,58	1,36	87,8	61,2
51-55	1986-90	0,83	2096-100	1,63	1,39	96,8	68,5
Mean		0,85		1,6	1,36	88,6	60,3

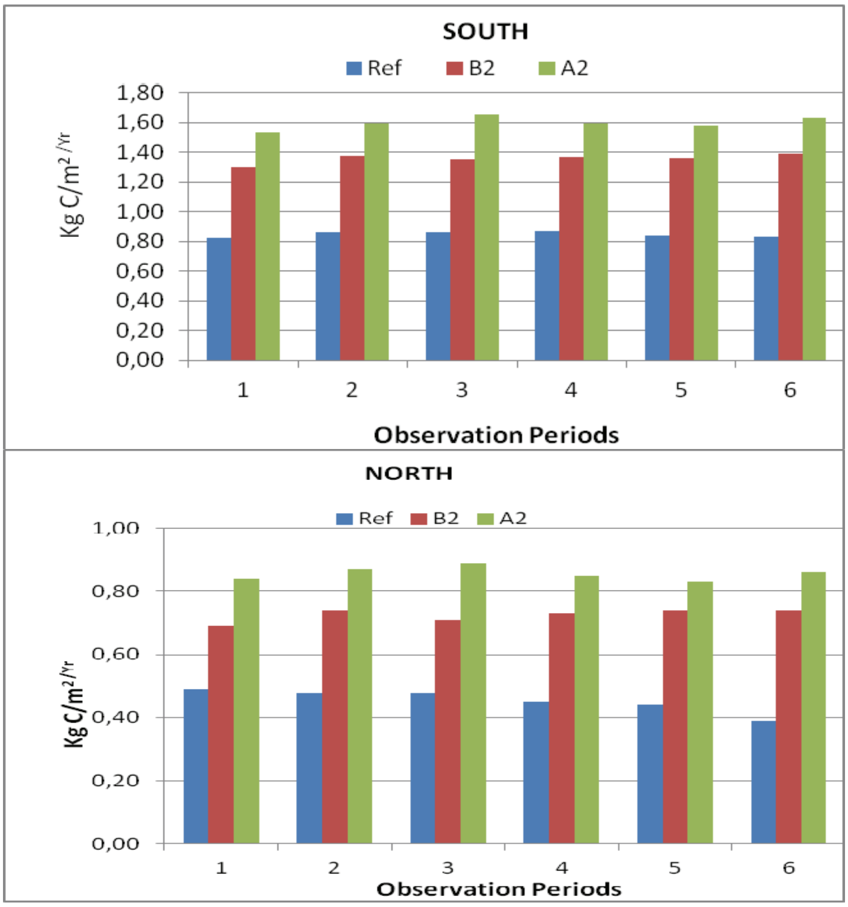

Figure 3 Comparisons of potential NPP predicted under the two scenarios against their reference time both for northern (lower figure) and southern (Upper figure) (Table 5 and 6).

4.2 Evaluation of 3-PG

4.2.1 Sensitivity analysis

Sensitivity analysis from climate normal years (1961-1990)

The response of the model for enhanced and reduced amount of rainfall is indifferent both for northern and southern Sweden. Exceptionally in southern Sweden it revealed a reduction of NPP by 0,043% with drop of rainfall amount.

An amount of 4,8% from temperature and 21,7 % from FR and 3% from temperature and 15 % from FR in northern and southern regions respectively was the average mean total NPP increment obtained when the model was run for elevated amount of the aforementioned factors. This trend was reversed in situations of reductions in input values. Subsequently, a relative mean reduction of 14,7 % and 27,3% as an effect of temperature & FR in northern and 11,7% and 17,4 % owing to temperature and FR in southern Sweden was observed from their corresponding value of climate normal years (Table 7).

Table 7 Relative change of NPP due to sensitivity test in northern and southern region from five years average values considering the reference scenario as the base year. The exercise is based on ±30% in temperature & ± 0, 2 in fertility rating. NPP is in kg C/m^2/year.

Years	Relative change in % due to sensitivity test of NPP in north				Relative change in % due to sensitivity test of NPP in south			
	Temp +	Temp -	FR +	FR-	Temp+	Temp-	FR+	FR-
1961-65	4,6	-12,5	16,9	-17,0	3,9	-11,7	14,9	-15,2
1966-70	5,1	-14,1	20,4	-22,8	3,3	-11,8	15,0	-16,8
1971-75	4,5	-14,4	21,2	-26,4	2,4	-11,7	15,2	-17,9
1976-80	4,8	-15,3	23,1	-30,2	1,5	-11,3	14,8	-17,7
1981-85	3,9	-15,3	23,8	-32,7	2,8	-11,7	15,1	-18,4
1986-90	6,0	-16,6	24,6	-34,8	3,4	-12,0	14,9	-18,2
Mean total	4,8	-14,7	21,7	-27,3	3,0	-11,7	15,0	-17,4

Sensitivity analysis from climate change years (2071-2100)

NPP predictions were independent of rainfall in both regions. There was no difference in the magnitude of NPP when compared with its initial value. However, a very little change i.e. a reduction of 0,003% of average NPP was experienced when the model is simulated for reduction of rainfall in A2 for southern Sweden. The additions of input values in the form of FR have raised the relative average NPP in northern and southern Sweden. An added amount of 17% in B2 and 15,8% in A2 from north and 13,5 in B2 and13,2 % in A2 from south are expected due to the change in FR. An increment of temperature enhances average NPP only in northern Sweden. The relative increase was 2, 4% in B2 and 2% in A2. In southern Sweden it led to a reduction of 0,2% in B2 and 1,8% in A2 scenario. The impact of reducing FR and temperature were ended up by decreasing the relative average NPP in both regions and scenarios. The reduced amount was 21% in B2 & 19 % in A2 due to FR and 11, 8 in B2 &

11, 3 in A2 owing to temperature in northern Sweden. In southern Sweden it was 14,4% in B2 & 13, 8 in A2 because of FR and 9,5 in B2 & 8, 6 in A2 due to temperature (Table 8 and 9).

Table 8 Relative change of NPP due to sensitivity test in southern region for both scenarios from five years average values considering the climate change scenario as the base year. The exercise is based on ±30% in temperature & ± 0,2 in fertility rating. NPP is in kg C/m^2/year.

Years	Relative change in % due Sensitivity test on NPP in south-A2				Relative change in % due to Sensitivity test on NPP in south-B2			
	Temp +	Temp -	FR +	FR-	Temp+	Temp-	FR+	FR-
2071-75	-0,2	-9,7	14,0	-14,6	0,3	-9,9	14,3	-14,8
2076-80	-1,6	-8,6	13,2	-13,9	-0,1	-9,5	13,5	-14,4
2081-85	-2,2	-8,2	13,1	-13,7	1,0	-10,2	13,4	-14,4
2086-90	-0,6	-9,2	13,0	-13,5	-0,2	-9,4	13,2	-14,1
2091-95	-1,3	-8,8	13,1	-13,7	-0,7	-9,2	13,3	-14,3
2096-100	-4,8	-6,9	13,0	-13,5	-1,3	-8,9	13,2	-14,0
Mean total	-1,8	-8,6	13,2	-13,8	-0,2	-9,5	13,5	-14,4

Table 9 Relative change of NPP due to sensitivity test in north region for both scenarios from five years average values considering the climate change scenario as the base year. The exercise is based on ±30% in temperature & ± 0, 2 in fertility rating. NPP is in kg C/m^2/year.

Years	Relative change in % due Sensitivity test on NPP in north-A2				Relative change in % due to Sensitivity test on NPP in north-B2			
	Temp +	Tem -	FR +	FR-	Temp+	Temp-	FR+	FR-
2071-75	2,4	-11,4	16,4	-17,1	2,0	-10,9	16,7	-17,2
2076-80	2,2	-11,4	16,1	-18,9	3,1	-12,2	17,3	-20,2
2081-85	1,9	-11,1	15,3	-18,7	3,9	-12,6	16,8	-21,0
2086-90	2,3	-11,5	15,7	-19,6	2,2	-11,9	17,4	-22,6
2091-95	2,2	-11,4	15,6	-19,7	1,8	-11,7	17,0	-22,6
2096-100	1,2	-11,0	15,6	-19,8	1,4	-11,6	16,8	-22,4
Mean total	2,0	-11,3	15,8	-19,0	2,4	-11,8	17,0	-21,0

The relative amounts of NPP reduced is high when parameter values of FR and mean temperature are reduced compared with the increment of NPP that is supposed to be earned with increment of FR & mean temperature in both regions, scenarios and base years (Table 7,8 and 9). Positive perturbation of FR and temperature in to the system resulted to more increment of NPP in northern than southern region and reference scenario than B2 and A2. It declined more in A2. The responses of regions and scenarios to the decline of FR and temperature are in the same trend as explained in the above paragraph but situation of NPP is in a decreasing order (Table 7, 8 and 9).

4.2.2 Validation of 3-PG

Results of total biomass of the two models did not respond exactly in a similar way in northern and southern Sweden. Total biomass values of 3-PG is slightly higher, almost equal to Heureka in southern region except the second from the last period. Heureka values are somewhat higher in northern Sweden for all periods of time (Figure 4).

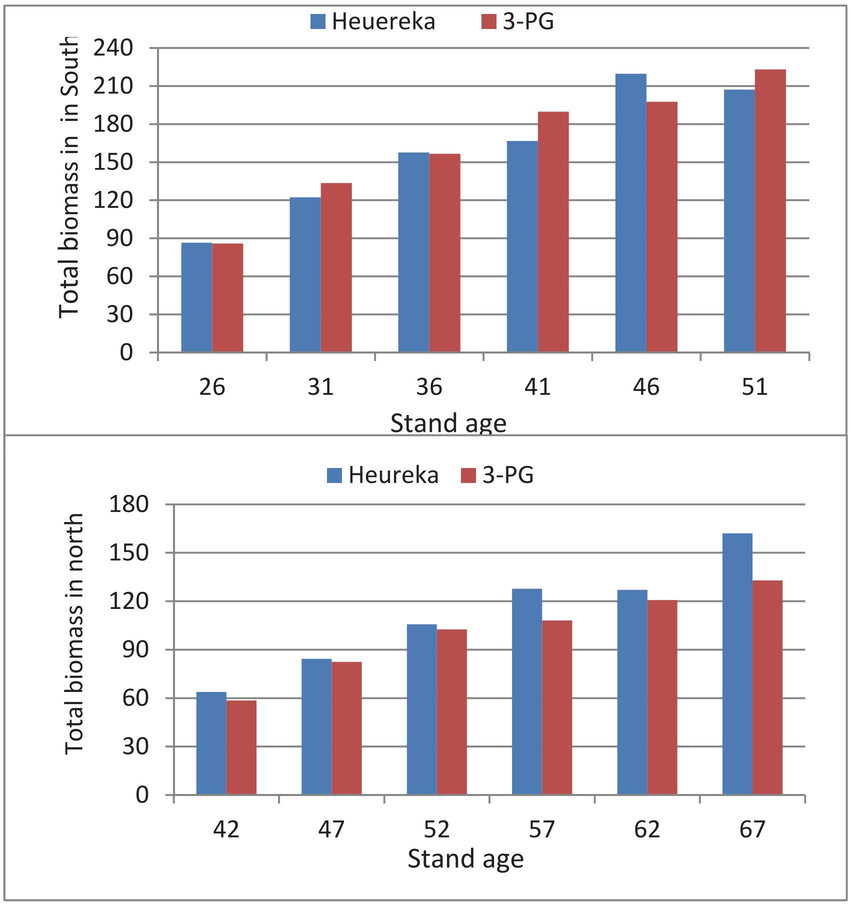

Figure 4 Comparison of total biomass of Heureka and 3-PG in tonnes DM/ha. The prediction values for 3-PG is using reference scenario and average values of five years.

The regression exercise between outcomes of the two models has found R^2 value of 0,94 & 0,9; AMB result explained the error with 8,6% and -3,2%; The MAD outcome confirms a variation of 8,6 % and 7% and the RMSE result suggested that 14,8 and 15,3 tonnes DM/ha mean distance were included between observed & prediction result of total biomass in northern and southern regions respectively (Table 10). The t-test shows absence of significance difference between outputs from the two models.

Table 10 Statistical tests of variation both in north and south region. The validation is based on reference scenario. The unit for MAD, AMB & RMSE are DM tonnes/ha

Region	MAD		AMB		RMSE		R^2	EF	t-test
	value	%	Value	%	value	%			
North	10,9	8,6	10,9	8,6	14,8	13,0	0,94	0,785	0,059
South	12,3	7,0	-4,5	-3,2	15,3	9,5	0,90	0,890	0,524

5 Discussion

5.1 Prediction of Net primary production

Simulation result of NPP of Norway spruce from 3-PG has shown an increment both in northern and southern Sweden in A2 and B2 scenario. This is essentially an effect of increased temperature which would contribute for increased N availability through mineralization & decomposition (Jansson *et al.*, 2008; Peng & Apps, 1999). The raise in temperature particularly in spring and autumn contributes for extension of growing season (temperature > +5 ^{O}C) and rapid recovery of winter damaged photosynthetic apparatus (Bergh *et al.*, 2003). The growing period is assumed to start in March in A2 during all periods for the southern region. In the B2 scenario, however, this is only true in 2096-2100; for the rest of the periods growing period commence in April instead. Considering the climate data for spring it entails that there would be an extension of growing period in north and south regions. This is also explained in a similar study of Bergh *et al.* (2010).

Besides, observed increase of temperature in spring would facilitate earlier budburst (Slaney *et al.*, 2007) in which both events would contribute to increase photosynthesis and growth (Bergh *et al.*, 1998). Delayance of frost nights in autumn, decline in its severity and frequency are the other effects of increased temperature. This will likely increase NPP in autumn(Bergh *et al.*, 2003). Had it not been counterbalanced from increased rainfall amount & ice melt the enhanced temperature would lead to increased evapotranspiration and moisture deficit with a subsequent negative effect on NPP. Likewise an increase of CO_2 concentration would have a likely impact on stomata closure which has a role to reduce water loss through transpiration (Kirschbaum, 2000).

Though studies claim about its transitory effect on growth (Körner *et al.*, 2005) one more justification for NPP increase is the raise in the concentration of CO_2 (Norby *et al.*, 2005; Bergh *et al.*, 2003; Peng & Apps, 1999). Analogous to the later the simulation result from 3-PG has shown an increment for enhancement of CO_2 throughout the simulation time. Overall the favorable situations with regard to temperature, moisture, frost cover reduction and availability of nitrogen might bring an improvement in LUE (Jansson *et al.*, 2008) and quantum efficiency (Landsberg & Sands, 2010) which is all due to climate change.

The result for the south region is almost close to the outcome attained from the study made by (Subramanian, 2010) with similar growth model which pointed out an increase & decrease of about 11% for A2 and B2 scenarios respectively. This is without considering the difference in climate model and sites considered in the two studies. It was not possible to compare the result of northern region to similar study done in the past, since there is no similar kind of study made using 3-PG as a process based growth model. On the other hand the higher relative increment of NPP in the northern Sweden compared to southern Sweden is in consistence with findings from other studies particularly Bergh *et al.*(2010). This might be due to relative higher increase in temperature in northern Sweden in autumn, spring & winter promoting availability of nutrients notably N and moisture due to mineralization and decomposition and snow melt respectively (Jansson *et al.*, 2008). It could also contribute for extension of growing periods(Bergh *et al.*, 2003). Besides, the study made by Bergh *et al.,*

(2005) showed that northern Sweden would allows more ‘potential and attainable production’ than southern if growth conditions were improved.

Higher level of atmospheric CO_2, relative increase in temperature and moisture, a decrease in frost days and snow cover in A2 than B2 contributes for acquiring more NPP in A2 than B2. These prevailing situations could allow the forest tree to utilize solar radiation due to higher temperature in early spring and late fall especially in the A2 scenarios. The decrease in snow cover is more noticeable in northern compared with southern Sweden (SOU, 2007).

Comparatively lower initial stand condition & suboptimal circumstances for growth in northern compared with southern Sweden during the reference scenario was reflected through lower increment at the initial period in northern Sweden. Less snow period and thickness during winter which mainly emanates from higher relative increase of temperature in autumn, spring & winter in northern than southern Sweden (Sonesson *et al.*, 2004) changed the situation and led to higher increment later in time. In relation to this, an experiment conducted to see the impact of a 5 ^{0}C growing season temperature increment in northern Sweden caused 15% and 60% stem wood production on fertilized and unfertilized plots (Sune Linder personal communication, August 18 th ,2012). This finding would give an idea about how the magnitude of production increment will be high when growing period enhancement combine with N availability in future climate change.

The highest potential NPP prediction from the simulation exercise is obtained during the last time steps (2096-2100) in both scenarios and regions. This is due to observation of the second higher temperature increment in winter in both scenarios and regions in that specific period of time and relatively better amount of summer rain fall particularly in June for A2 and B2 and July of B2 in south.

Though the period between 2086 and 90 recorded the highest winter temperature increment in south both in A2 and B2 scenario, the relative increment of NPP is the lowest of nearly all the periods (Table 3, 4 and 6). This could be explained from the fact that there happen rare cases whereby growth in forests primarily increase within the commencement of change in climate nevertheless there will be a decline in production when the temperature gets warmer (Sonesson *et al.*, 2004). This is compatible with the results of sensitivity analysis in south. Besides, it is in line with the silviculture of Norway spruce where normal physiological process is going to be affected by warmer climate (Sonesson *et al.*, 2004). As to this test perhaps, the upper limit for optimum temperature in south would be the temperature increment that will take place during winter of 2096-2100 (Table 4).

The relative increment in NPP from the reference scenario using 3-PG is higher than previous studies conducted using other PBM like boreal adapted version of BIOMASS in Sweden (Bergh *et al.*, 1998). In former studies it was found that there will be an increment of 0-50% of NPP due to climate change depending on stand age and site condition (Sonesson *et al.*, 2004). This disagreement in magnitude might be due to quite high leaf area index result from 3-PG which is a key parameter as it is highly related with APAR (Fontes *et al.*, 2006). An amount of up to 6 and 7 and 11 and 13 LAI outcomes were obtained in the last years of the simulation time in north (B2 and A2) and south (B2 and A2) scenarios respectively. However, the default value of LAI for coniferous after thinning in Sweden is about 5-6 (Johan Berg, personal communication, June14 th, 2012). Thus this increased value of LAI is assumed to contribute for enhanced growth in 3-PG especially in southern Sweden though its contribution for NPP after the 8th number of LAI is only less than 2% (Landsberg & Sands, 2010).

An additional argument would be the different courses of processes, approaches and arithmetic's and capacity of prediction involved with in the models; for instance 3-PG depend on carbon balance equation(Sands, 2004) which is highly sensitive to climate change situations and fertility than procedures used in BIOMASS. Therefore, its sensitivity to the above factors could be reflected in the magnitude of output of the simulation under climate change. In addition, presence of fed back mechanisms of soil nutrient process in 3-PG which is absent in BIOMASS (Sonesson *et al.*, 2004) would be also one more factor for difference in NPP prediction between the two models.

In summary, NPP prediction between northern and southern Sweden varies demonstrating determination of climate motivated processes on forest growth and development (Peng & Apps, 1999). Besides, the result of this study is in an agreement with other similar studies in the broad sense of pattern of increment of predicted potential NPP both temporally and spatially save the difference in predicted amount of NPP. The reasons for this could be analyzed in the future by detail examination of the data & model behavior. However, this does not mean that the result from this simulation is unacceptable for the fact that the simulations were went through consideration of climate change which is full of complex events & uncertainty. Moreover, the comparison is also from different models which are potentially with different behavior. On the other hand, the statistical tools result recommend to rely 78, 5% for north and 89% for south in predictive capability of 3-PG when compared with Heureka StandWise which is with prediction error of 0,2 (Elfving & Nyström, 2010). A point to note in regard to this is, looking outside Sweden a simulation undertaken with yield and growth model under the face of climate change led for an increment of 170% and 56% in northern and southern Finland correspondingly (Bergh *et al.*, 2006). The increment is almost in equivalent form of biomass (Johan Berg, personal communication, August 22th, 2012). The simulation outcome in northern Finland is by far higher than the simulation in this study.

5.2 Evaluation of 3-PG

5.2.1 Sensitivity analysis

The reaction of the model for climate normal and climate change years, for the two scenarios and regions are similar in trend. Mostly there was negative increment for the reduction and positive increment for the increment in input parameter values. However the outcome for temperature increment in A2 and B2 scenarios for southern Sweden and increment and decline of rainfall for almost all of the components perform differently. There was an observed difference in magnitude of reduction & increment in production. In this regard, higher reduction and increment is noticed while considering the climate normal years as an initial point than climate change years and reference scenario than B2and B2 than A2.

Even if, there are problems to determine how to interpret the result from the sensitivity analysis (Elston, 1992), a simple scheme of comparisons based on the magnitude of the impact from this work denote NPP is more sensitive for FR than temperature and rain fall. Rainfall is not detrimental in predicting NPP. This situation is in parallel with studies conducted earlier confirming the higher sensitivity of the model to FR (Esprey & Smith, 2002).

The response of the model for enhanced and reduced amount of rainfall is indifferent in regions, scenarios and climate normal & climate change years. This therefore shows that relative sensitivity of NPP prediction is almost zero indicating the non sensitivity of the model output to rain fall. The independent of NPP to rainfall on the other hand tells that sites are not very much water limited. There would be other sources of moisture that can back up forest production like melting of snow and residual of excess moisture outside the period considered for sensitivity test as the soil water balance component of the model considers moisture stored in the soil earlier in time (Coops *et al.*, 1998). In relation to this, though it is little the down side effect we saw in NPP prediction due to reduction of rainfall from the climate normal years and A2 of the climate change years in south could be an evidence to substantiate the existence of moisture constraint to forest production in the area.

The introduction of positive and negative value of FR in to the system has brought a relative higher growth rate and decline in NPP prediction respectively in northern than southern Sweden in both climate normal and climate change years. The same analogy works in reference than B2 & B2 than A2 scenarios in both regions. This FR sensitivity analysis outcome would be an evidence for constraint of nutrient in north. The situation in the reference and climate change scenarios also indicates the presence of variability of nutrient status which is related with temperature & CO_2 concentration. The higher reaction rate in terms of amount of NPP for negative & positive changes of parameters in the reference scenario is due to relative lower level of nutrient status in the reference than B2 & A2. The reaction becomes moderate in B2 and gets relatively lower in A2 as the nutrient status is approaching to the upper limit of the optimum. The increment of NPP both in northern & southern region with rise of FR values indicates that FR value did not reach a level of constraints to production ('diminishing return') through the simulation period.

Smaller increment of NPP for positive change of temperature from climate normal years is observed in northern & southern region and from climate change years in northern Sweden. The relative increment of NPP in the reference scenario is higher in both regions than to the climate change scenario, likely due to large contribution of increased temperature to NPP in reference scenario than climate change scenario.NPP is declined for the positive change of temperature induced in to climate change years in southern region. The circumstances in southern region implies that NPP increases with increasing temperature up to a certain level that is considered optimum for the process and then declines (Landsberg & Sands, 2010). This reflects existence of higher temperature background in southern than northern Sweden which has contributed for reaching a point of diminishing return before northern region. Therefore this asserts production in southern region is limited to some extent due to water stress (Bergh *et al.*, 2010). Here it would be logical to remember what happen to the sensitivity test of rain fall reduction in southern Sweden in which both assertions would provide a room to reach in to the above persuasive conclusion about the background of the region. From the analysis one can speculate the point of the upper limit for optimum temperature to be around 18-22% temperature increment (which is □ 30% standard of the sensitivity analysis) from the changing scenarios both in A2 and B2 in the southern region. The pattern of the response in terms of NPP for reduction of temperature is higher in the reference than climate change scenario in both regions. This is probably due to lower level of temperature & moisture in the reference scenario thus further reduction to this benchmark temperature value resulted to more decline in NPP.

The results presented above indicate sensitivity of the factors considered in the exercise are site dependent as the sensitivity result is assuming a variation within the ranges of the two regions; which is in compatible with studies done by Battaglia & Sands (1998). This further stressed the importance of including more environmental conditions when validating a model (Hackett & Vanclay, 1998) or analyzing its structure (Battaglia & Sands, 1998).

In general the sensitivity analysis in this study attests that FR and temperature has been found influential driving variables in either direction while predicting NPP across the two regions. This indicates that FR and temperature needs to be estimated precisely with particular consideration to depend on the model for practical application in Sweden for Norway spruce in future time. It also emphasized the existence of moisture and nutrient problem in south and north correspondingly.

5.2.2 Validation of 3-PG

Total biomass values of 3-PG is slightly higher and almost equal to Heureka in southern Sweden except the second to the last period. Heureka values are higher to some extent as well in northern region in all periods of time. The variation is pronounced more after thinning. The evidence for this variation is unclear. Nevertheless, it could be due to the different initial stand condition of the sites, various ways of interactions and reaction of the models. Perhaps the relative higher fertility rating value attached to southern than northern region might contribute for enhancing above ground growth in 3-PG (Landsberg & Sands, 2010). This does not mean that the difference in nutritional status of the regions was not treated in Heureka as well. It is considered in terms of SI value. Apparently, estimation of nutritional status of the two region using SI values in Huereka and FR values in 3-PG might not reflect the nutritional status of the regions in equivalent ways. Absence of clear guideline to fix FR makes the exercise cumbersome (Landsberg *et al.*, 2003). In this regard an attempt to look for variation in total biomass, simulated using the same model from each region, resulted with slightly higher value differences in 3-PG than Huereka with in all similar period of time except for the second period next to the last. Based on this, one can say that the response of the models to this input factor (expressed in SI & FR) may be different probably 3-PG has over estimated growth due to fertility in south (productive area) and under estimate in north(low productive area).

An additional argument for this small disparity to happen could be their response to thinning in a different manner. The effect of thinning in Heuerka was observed late while in 3-PG it was manifested early. Due to the above fact it was not able observe the outcomes of the second thinning operation from Heureka StandWise in southern Sweden as it was done one period before the simulation cycle is to end. These have probably added a value for the enhancement of variation of output values in periods of time after thinning. On the other hand Sands (2010) noted that '3-PG does not appear to respond correctly to thinning or defoliation particularly in relation to biomass partitioning after the event'. Therefore this argument would have contributed for the variation in total biomass from the two models particularly after thinning.

Despite these complex processes with positive and negative fed back mechanisms within the two models, the comparison exercise has found R^2 value of 0,94 & 0,9 for northern and southern Sweden. This tells that 3-PG is able to express about 90% of the observed variation in this prediction in both regions; the rest can be explained as an error originated from different sources.

The AMB with capability to express the anticipated error of the average or total values of the observation (Pinjuv *et al.*, 2006; Vanclay & Skovsgaard, 1997) has explained the deviation with 8,6% and -3,2% in northern & southern regions respectively. This measure however is 'not true measure of deviance' as values which are greater and less than zero are balanced with each other (Mayer & Butler, 1993). The MAD outcomes which are the average error from each single prediction (Vanclay & Skovsgaard, 1997) were found to be 8,6% for northern and 7 % for southern Sweden. This is in similar range with result found in Asa. Average bias between -3 to 15% were found by simulated values of standing volume (Landsberg *et al.*, 2003). The AMB and MAD values entails that in north the error both from single prediction and average /total are similar whereas the error in south is more evident when it is considered from each single prediction than total or average. Positive values of AMB and MAD in north illustrate that the total biomass value of the prediction is less than the observed (underestimation of 3-PG). On the other hand the negative value of AMB in south explains existence of higher value from the prediction than observed (over estimation of 3-PG).

The RMSE result suggested 14,8 and 15,3 tones DM/ha mean distance were included between observed & prediction result of total biomass in north and south regions respectively. Larger errors will have relatively higher weight in RMSE measurement(Janssen & Heuberger, 1995) . The modeling efficiency explains the observed variation by 78,5 % & 89% in north and south regions respectively. This is in close proximity suggested by some previous studies (Nolè *et al.*, 2009; Stape *et al.*, 2004; Coops *et al.*, 1998). The slight higher modeling efficiency value of southern to northern region is due to presence of relative higher variance & standard deviation both in observed and predicted total biomass due to the effects of larger values as the errors are calculated squared(Mayer & Butler, 1993).

To encapsulate, the various statistical tools demonstrate that the total biomass from the two models are in good agreement, not significantly different and the deviations are normally distributed. Albeit the acceptable level depends on the purpose, scale of the simulations and model type (Härkönen *et al.*, 2010) in this work since the RMSE and MAD values are lower than half of the standard deviations of total biomass the values may be assumed low and it might be reasonable to use the model for prediction (Singh *et al.*, 2004). It as well meets the upper limit criteria of 10% for MA%D set by (Huang *et al.*, 2003; Kleijnen, 1987). The modeling efficiency is also within acceptable model performance range (Moriasi *et al.*, 2007).

These coupled with the flexibility, non site specific behavior of 3-PG and the experience the model went through the various validation exercises using various tree species (*Betula Platyphyela, Pinus radiata, Pinus taeda, Pinus patula,Pinus sylvestris, Picea abies, Cunninghamia lanceolata, Eucalyptus nitens, Eucalyptus grandis, Eucalyptus globules, Pinus ponderosa*) , spatial distributions (Japan, Finland, Sweden, Portugal, China, Spain, UK, New Zealand, Australia, Brazil, Chile, Canada, South Africa, USA) (Potithep &

Yasuoka, 2011; Landsberg & Sands, 2010; Rodríguez *et al.*, 2009; Zhao *et al.*, 2009; Fontes *et al.*, 2006; Landsberg *et al.*, 2005; Almeida *et al.*, 2004a; Dye *et al.*, 2004; Landsberg *et al.*, 2003; Rodríguez *et al.*, 2002; Sands & Landsberg, 2002; Stape, 2002; Landsberg *et al.*, 2001; Law *et al.*, 2000) & climatic conditions (temperate, sub tropical and tropical) with 'useful accuracy' (Landsberg *et al.*, 2003) would be an asset to recommend the model to be used as an application management tool to predict NPP in Sweden as far as parameters and input values are properly determined. More specifically, issues like thinning, determination of FR and outcomes of LAI should be dealt with maximum care. Furthermore replications of the evaluation exercise with other species parameters and model input data than dealt here might be vital.

6 Conclusion

The results from the statistical tools reveal the good performance of 3-PG. It showed that the model can be used to predict NPP in Sweden. However, thinning operation, determination of FR and outcomes of LAI should be taken in to account. Additionally, the model should be evaluated further by incorporating other species parameter and model input data to recommend it as a forest management tool. This is helpful since such kind of research using 3-PG is rare in the area. According to the prediction from 3-PG, the mean relative increment of mean total NPP after 110 years of time is 89, 7% & 60, 5 % for A2 and B2 in northern and 88,6% & 60,3% for A2 and B2 of southern Sweden respectively.

Even though it is difficult to precisely determine the magnitude of the increment from its reference time, it could be intuitively suggested that there might be an increment in the magnitude of NPP from Norway spruce in Sweden due to climate change. This enhancement has positive implication for the national economy of Sweden where forestry has a considerable role. Nonetheless, to obtain the actual net benefit there is a need to scrutinize the deleterious effect of climate change which is not touched in this paper perhaps would be an area of further research. To extract the benefit from the existing opportunity, preparedness is needed in Sweden. This indeed may bring a change in forest and risk management which is another wake-up call for further investigation. By and large, the strategies should best suit with the expected climate change to take out the merit from the new opportunity.

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Acknowledgements

I would like to thank my main thesis supervisor Narayanan Subramanian for his competent guidance and support throughout the completion of this work. E-mail correspondence, telephone conversation and discussion both at his office & coffee room in the first floor of the building in Alnarp was unforgettable. Each of them was fundamental for the success of this work. Not only our discussion was limited to this thesis, but also it went to the extent of future career. He was so flexible in arranging discussion time to the extent of sacrificing his weekends.

I am indeed indebted to Dr Johan Bergh, who served me as co-supervisor, for the critical role he played during different phases of the work and for his valuable comments and constructive criticism. I am also grateful for Dr Peter Sands, who had rewritten the software for 3-PG, for sharing me his rich experience with regard to 3-PG model while I face some difficulties. I remain thankful to Professor Ola Sallnäs for his valuable comments with modeling and forest growth and development which were helpful to determine the parameter to be considered in this thesis. I remain indebted to Dr Per Magnus Ekö and Dr Eric Agestam for their support and encouragement in different ways. I would also like to thank my special friends Seid, Setegn , Mulugeta and Amare; the experience we share through our dialogue about thesis, development work and overall to our common interests have been more stimulating and encouraging.

My wife is always standing beside me. Her motivation to pursue my education has reached me here and helped to know the inner me more. I am highly indebted to her understanding in discharging the difficult task of parenthood and other responsibilities alone when I was devoting more time on my study. I remain indebted to my family, in-laws, Aba Seregela and Aba Fikremariam for their prayer support. Above all I must extend special thanks to the ALMIGHTY GOD for everything of merits are due to his good will. This piece of work is dedicated to you, my beloved wife, Meseret Menil Abitew.

Gizachew Tarekegn Getahun

Appendix Important parameters values in 3-PG for Norway spruce

Description of parameter	**3-PGPJS name**	**Units**	**Value of Norway spruce**	**Reference**
Biomass Partitioning and turnover				
Allometric relationships & partitioning				
Ratio of foliage stem partitioning at D=2cm	pFS2	-	0,8	
Ratio of foliage stem partitioning at D=20 cm	pFS20	-	0,7	
Constant in the stem mass vs diameter relationship	aS	-	0,025	
Power in the stem mass vs diameter relationship	nS	-	2,82	
Maximum fraction of NPP to roots	pRx	-	0,9	
Minimum fraction of NPP to roots	pRn	-	0,26	Livonen *et al.,* 2008
Litter fall and root turnover				
Maximum litter fall rate	gammaFx	1/month	0,014	
Litter fall rate at t=0	gammaF0	1/month	0,001	
Age at which the litter fall has median value	tgammaF	Months	24	
Average monthly root turnover rate	gammaR	1/month	0,0096	
NPP and conductance modifiers				
Temperature modifier (fT)				
Minimum temperature for growth	Tmin	^{O}C	-3	Bergh *etal.*, 2003
Optimum temprature for growth	Topt	^{O}C	20	
Maximum temprature for growth	Tmax	^{O}C	43	Bergh *etal.*, 2003
Frost modifier(fFRost)				
Days production lost per frost day	KF	Days	1	
Soil water modifier(fSW)				
Moisture ratio deficit for f_{θ} =0,5	SWconst	-	0,6	
Power of moisture ratio deficit	SWpower	-	7	
Age Modifier				
Maximum stand age used in age modifier	MaxAge	years	120	
Power of relative age in function of fAge	nAge	-	3,675	
Relative age to give fAge=0,5	rAge	-	0,95	
Stem mortality and self thinning				
Mortality rate for large t	gammaNx	%/year	1	
Seedling mortality rate(t=0)	gammaN0	%/year	0	
Age at which mortality rate has median value	tgammaN	Years	35	
Max stem mass per tree at 1000 trees/ha	wSx1000	Kg/tree	300	
Power in self thinning rule	thinpower	-	1	
Canopy structure and processes				
Specific leaf area				
Specific leaf area at age=0	SLA0	M^2/Kg	5	Bergh *etal.*, 2003
Specific leaf area for mature leaves	SLA1	M^2/Kg	3,5	Bergh *etal.*, 2003
Age at which specific leaf area=(SLA0+SLA1) /2	tSLA	M^2/Kg	3	
Light interception				
Age at which canopy cover	fullcanAge	Years	10	Eliasson *et al.,* 2005
Wood and stand properties				
Branch and Bark fraction				
Branch and bark fraction at age 0	fracBB0	-	0,25	
Branch and bark fraction for mature stand	fracBB1	-	0,15	

Age at which (fracBB=fracBB0+fracBB1)/2	tBB	years	3
Basic density			
Minimum basic density for young trees	rhoMin	t/m^3	0,400
Maximum basic density for older trees	rhoMax	t/m^3	0,400
Age at which (rhoMin+rhoMax)/2		years	60

Source: Subramanian, 2010