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The economic value of the effect of weather variability on forest ecosystem services in Sweden

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Abstract

In Sweden, production forests primarily consist of planted coniferous trees often mixed with naturally regenerated broadleaves. The predominating boreal conifer species are Norway spruce, and Scots pine which constitutes 40.8% and 39% of the total productive forests cover respectively. This thesis aims to estimate the effect of weather variability and management practices on forest productivity and to calculate the total economic value of forest ecosystem services of timber and carbon sequestration in Sweden. The analysis is carried out in two steps. Firstly, to estimate the impact of weather conditions and management treatments on forest growth using a theoretically sound linearized logistic growth model. Secondly, to quantify the total economic value of the timber and carbon sequestration based on their unit net prices using the static additive model approach.

The findings suggest that forest productivity in the boreal region increases with the rise of temperature and the length of the vegetation period. Also, the management system of scarification contributes to the increase in standing volume per hectare. The long-term effect of scarification can last from the beginning of young planted seedlings until they reach high levels of productivity. Accordingly, the increase of weather variability of temperature and the length of the vegetation period on forest productivity contribute to the total economic benefit mainly through the incremental value of carbon sequestration. The total economic value in the base scenario is reported to be SEK 1065/m^3/ha. In average, the total value increases by about 11% with a one-unit increase of temperature and around 1.5% with a one-unit increase of the length of the vegetation period relative to the base scenario. However, the value of timber remains constant and equals to SEK 923/m^3/ha in all calculation scenarios.

In 2018, the economic value of timber production in the entire country constituted 23% of the gross domestic product (GDP). Because of the nature of local weather conditions which vary across different regions in the country, this study could not easily estimate the overall total economic value of both timber and carbon sequestration at a national level. The results of this study provide incentives for future research to use mathematical relationships that could not only capture potential economic benefits but also would optimize management decisions which produce long-term impact on sustainable forest ecosystems.

Abbreviations

CO_2e – Carbon dioxide equivalents.

FMOLS- Fully Modified Ordinary Least Square

GHG- Greenhouse gases

Ibid – ibidem (in the same thesis).

mm- Millimeter

NPP- Net Primary Production

SMHI- Swedish Meteorological and Hydrological Institute

Table of Contents

List of figures

List of tables

1 Introduction

The forestry has long been an important sector that offers various benefits to society. In recent years, dramatic changes in the forestry industry have vastly increased because of its multiple uses such as commercial value, maintaining national biodiversity, importance in water catchments, and carbon sequestration. These changes are partly due to significant impacts of climate variability on forest growth and its compositions (Coops *et al.* 1998). Thus, the management of forest resources should seek the balance of yields from as many benefits as possible. Furthermore, we should move beyond maximizing the merchantable biomass and find answers to several optimization questions regarding the benefits provided by forest ecosystems. To understand the total economic value, we need to consider the expansion of these paramount ecosystem services.

1.1 Problem background

Swedish forests are even-aged monoculture with the primary dominating boreal conifer species of Norway spruce (Picea abies(L.) Karst.) and Scots pine(Pinus sylvestric L.). The principal forest management practices are fertilization, scarification, and thinning in the entire country. Furthermore, total harvesting of the entire stands and re-planting new seedlings are massive operations of intensive management systems. On the other hand, weather variability is an essential factor that affects forests in different ways. For example, a rising temperature could affect the forest in two ways: by changing forest productivity of the actual forest biomass or by changing forest distributions in different geographical areas (Eriksson & Vesterberg 2016). A slow but continuous rise in temperature could also have different impacts on forest site conditions resulting in the increasing of forest productivity which is then, at a certain threshold, followed by a loss of carbon storage due to an elevated temperature (Daly *et al.* 2000).

The forest cover is more than half of the country's total land surface, meaning that the forestry sector is of a great contributor to the national economy. For instance, Sweden is the 5th highest combined exporter of pulp, paper, and forest products, after the United States, China, Germany, and Canada. The Swedish forest industry represents about 10 percent of exports, revenue, employment, and value-added of the entire economy (WITS 2017).

In their study of managing forest in uncertain times, Bellassen & Luyssaert (2014) pointed out that there is a shortage of knowledge of the impacts of temperature similar to any other weather patterns such as precipitation on tree growth. They found that changing forest management practices is of great importance only at the local level (national and regional) not at the global level. The present study aims to estimate the total economic value of forest ecosystem services from the effects of weather patterns and management practices on forest productivity in Sweden for about 50 years.

1.2 Problem statement

The long-term forest management decisions that seek to maximize economic value should consider weather variability as an essential factor in the dynamics of forest growth. Forest trees in boreal zones are growing below the optimum weather conditions, and therefore, they react with a higher growth rate to an increase in temperature (Way & Oren 2010). However, under extreme weather conditions, there is a high risk that they will respond with a substantial fall in the growth rate (Scholze *et al.* 2006). These dynamics of forest productivity due to weather patterns and management practices have consequences of variations in the economic development of the sector. This investigation of the effect of weather patterns and silvicultural systems on forest growth is indeed intended to take the current scientific knowledge to another level. The motive is to understand their contribution in changing the forest growth rate and the overall magnitude on the entire ecosystems, which in combination will serve for quantifying the total economic value of forest ecosystem services.

1.3 The objective of the study

The main objectives of this study are, therefore, to (i) estimate the effects of forest management practices and weather patterns on forest growth. Furthermore, (ii) quantify the total economic value of timber and carbon sequestration provided by forest ecosystems in Sweden (see fig.1).

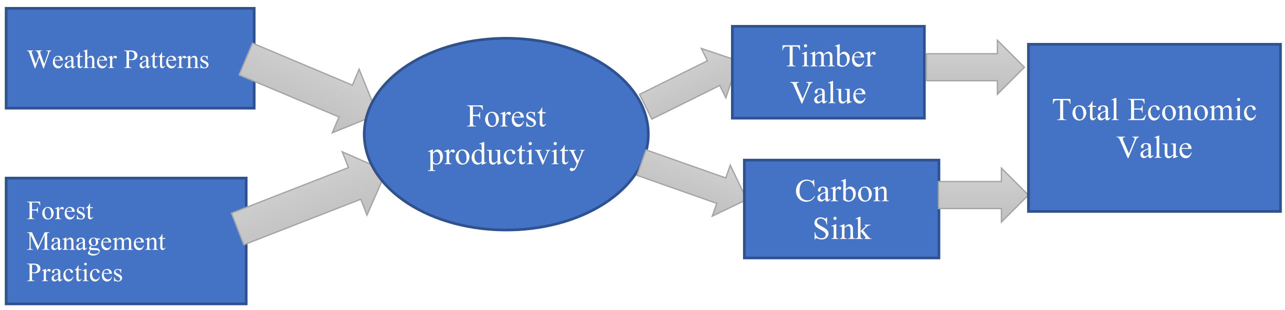


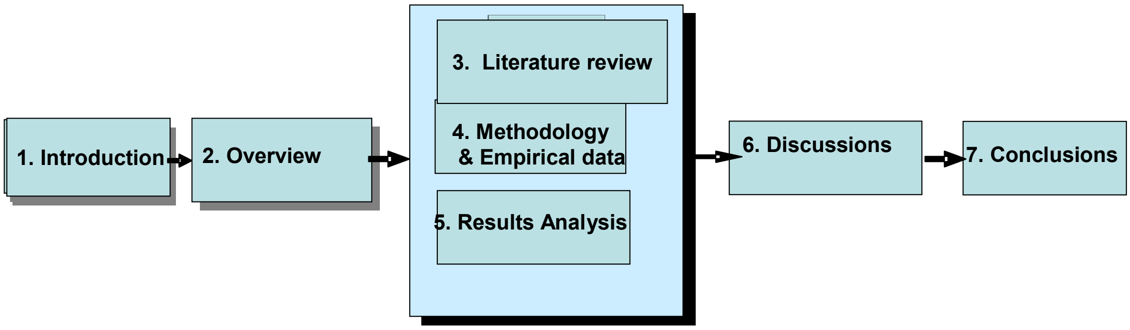
Figure 1. The process of calculating the total economic value.

The panel data on forests, weather patterns and intensive management practices in four regions of Sweden; norra Norrland, södra Norrland, Svealand and Götaland, (see figure A1) were used, starting from 1965 until 2013, to assess the effects of weather variability and silvicultural practices on forest growth using econometric modelling. It is then followed by quantifying the total economic value of timber and carbon storage using their respective unit process with the additivity approach.

1.4 Disposition

The rest of the work is organized in the following way to achieve the objectives of the thesis. Section 2 presents an overview of forest management practices and weather conditions. Section 3 reviews the literature. Section 4 illustrates the methodology and empirical data of the study, and section 5 describes analysis of the results, which is then followed by section 6 that presents discussions. Section 7 presents conclusions (see fig. 2)

Figure 2: Structure of the thesis



2 Overview of forest management practices and weather conditions in Sweden

2.1 Forestry Industry in Sweden

The forest industry is one of the critical pillars of Sweden's business sectors and provides tens of thousands of jobs throughout the country. More than half of Sweden's total land area is the forest, with approximately 23.50 million hectares of productive forest land, and 4.62 million hectares of unproductive forest land. The most dominating tree species are spruce and pine each constituting 40.8 % and 39% of the total forest land, respectively. Forest resources productivity has doubled over the last 100 years, while forest harvest is about one percent of what is produced every year (Nilsson *et al.* 2018). Furthermore, the forest industry depends heavily on export market orientation with possible variations between 9-12% of the exports, employment, turnover and value addition compared to the relatively small share of import of forest resources and use of raw materials in the entire industry in Sweden. Also, this industry accounts for 17% of the total manufacturing sector (Nolander, 2018).

2.2 Forest Ecosystem Services

Sweden has intensive forest ecosystems resulting from its special weather conditions. To some extent, this is because the country experiences yearly winter frozen conditions and that there are relatively few tree species, unlike the diversity of corresponding forest ecosystems around the world. The habitats in the boreal forest follow a random walk of temporal changes of various environmental conditions, caused for example, by forest fires, and storms. However, these natural disturbances have experienced regular control over the last decades because of the well-organized development of the forestry industry (SFA 2015).

The forests play an essential role in binding carbon emissions that have gone into the atmosphere. While global forests suck up 30% of anthropogenic emissions every year, the Swedish forests offset more than 80% of the total country's emissions (Nolander 2018; *LULUCF* 2018). Carbon sequestration is an excellent and most prominent regulatory forest ecosystem service. Usually, it takes the value of either taxpayer-subsidies related carbon emissions or the social costs associated with greenhouse gases emissions (Brainard *et al.* 2009).

Besides that, forest carbon flow is a very complex mechanism of forest ecosystems. Some drivers of this flow process are, for example, weather variability, tree species, geographical location, and silvicultural treatments (Bellassen & Luyssaert 2014).

Also, carbon sequestration is the most critical ecosystem service provided by forests at least in recent years. The geographical location of forest plantations does not matter since the amount of carbon storage benefits at large scale around the globe. The annual storage of carbon emissions, mainly carbon dioxide, determines the fundamental value of this ecosystem service associated with the volume of growing tree biomass and the soil nutrients (Nolander and Lundmark, 2018; Brainard *et al.* 2009). It is worth noting that various tree species have different rates of growth, and accordingly, the amount of carbon sequestered is expected to vary with species. Additionally, the warmer the temperatures, usually the better conditions for trees to grow and to increase carbon storage.

2.3 Forest Management Practices

Forest management practices are mostly performed with the purpose to increase the productivity of tree biomass since these management activities lead to a higher net primary production of the stem-wood. Similarly, these practices reduce the level of heterotrophic respiration because parts of biomass removals perish and decay. As a result, it turns out that the effects of silvicultural treatments such as thinning and harvesting contribute to regulating carbon emissions (Luyssaert *et al.* 2007). It shows that forest site quality changes over time with the choice of management treatments and have significant effects on forest growth and therefore changing profitability.

The current Swedish forest policy constitutes two equally important main objectives linked to the legal request for intensive management practices. The first objective focuses on the increase of timber production, and the second objective equally well supports biodiversity conservation (SFA 2015). Several studies have questioned the optimal management practices that would drive towards maximization of carbon storage because the optimal rotation ages are estimated to be longer when they are associated with carbon sequestration, and they are shorter for optimal harvesting decision. Hence, the prevailing hypothesis that bioenergy is a net-zero carbon footprint is challenged (Bjørnstad & Skonhoft; McDermott *et al.* 2015).

2.3.1 Fertilization

In Sweden, fertilization in forest sector was introduced in the late 1960s after extensive and thorough studies connecting various aspects of the boreal forests including physiology, yield, ecology, and nutrient (Tamm, C.-O, 1991; Enander KG, 2007). However, forest fertilization did not develop intensively as an operational management practice until the 1970s when fertilizers were used in more than 200 thousand hectares and then started dropping in the 1990s (Lindkvist *et al.* 2011). The analysis carried out for Holmen Skog AB indicated that while the selection of tree species and improved planting materials have substantially increased profitability with reasonable outlay in costs, fertilization proved to be much more profitable.

Using forest fertilizers to increase tree biomass of Norway spruce was proved to be non-beneficial since it generates high cost at the beginning of the project (Eriksson *et al.* 2008). Therefore, the Swedish forest sector almost abandoned fertilization as a management practice. This is not only because it incurred higher investment cost but also because of its detrimental impacts on the environment. Despite the high costs and adverse effects on the environment, fertilization has regained popularity among Swedish forest owners in the past decade. Since 2010, statistics reports show that its consumption in the forest is at an all-time high (Nilsson *et al.* 2017). The current political agenda endorses the use of forest products. It also promotes non-fossil fuel (biofuels). These are incentives to boost the forest sector, which is one of the driving industries of the national economy, then also challenging global warming at a massive scale.

2.3.2 Thinning

Thinning as forest management activity aims to enhance forest productivity, then boosting the profitability of the forest industry. This primary method has been used in Swedish forests over the last 200 years, most notably “thinning from below” (Wallentin 2007). Yet, several thinning studies have concluded that thinning methods also hurt total forest productivity. For example, there is a negative correlation between the growth of Norway spruce and Scots pine and the average amount of removals from a particular basal area (Makinen 2004; Mäkinen & Isomäki 2004; Nilsson 2010). Some exceptional of spruce species respond to light and moderate thinning by developing high tree volume productivity (Juodvalkis *et al.* 2005).

The thinning leads to a decrease of stand density which in return induces the remaining part of the tree to grow competitively relative to other available factors such as the nutrients, water and solar radiation (Savill 1997; Larson *et al.* 2001). Usually, we would not expect the thinning to raise the total productivity per unit area, but to some extent thinning would contribute to the development of high growth rate of trees and the yield of the log-sized timber (Makinen 2004; Mäkinen & Isomäki 2004). The beneficial effects of thinning depend on the amount and value of the removals, timing, and magnitude of precommercial thinning with additional costs of clear-cutting (Huuskonen & Hynynen 2006). In the forest sector, the intensity of thinning was improved during the 1960s, reflecting the mechanization of harvesting practices. In Finland for example, caring for younger forest stands is done at least in three successive thinning operations throughout the entire rotation period which can usually last up to 80 years (Tapio 2013)

2.3.3 Scarification

Scarification has been the most popular and uninterrupted management method used in trees plantation in different parts of the country and has proved to be successful practice for various tree species (Nilsson *et al.* 2011, 2018). This mechanical management practice consists mainly of two different major categories: disc trenching and mounding. The former is suitable in all four different agro-ecological zones of this study, and the latter can be applied basically in an environment with enough moisture and moderately stony soils. These two method categories produce different quality of forest plantations. The differences are attributed to the particular quality of the forest site and other bounding factors linked to these practices (Örlander *et al.* 1990). While disc trenching generates insufficient nutrients and an excess of water compared to what plantations need, mounding could increase the probability of drought stress specifically in newly established plantations on highland spots (Nilsson & Örlander 1999).

Thus, applying these two silvicultural practices can have from short term to long term adverse effects due to a sharp decrease of nutrients as well as to a high degree of the site disturbances (Johansson 1994). Nevertheless, introducing soil inversion as another type of scarification reduces the adverse effects caused by the previous two methods.
The purpose is to level seedlings planting spot and the nearest soil ground so that the early planted seedlings will develop desirably (Nordborg *et al.* 2003; Johansson *et al.* 2006, 2013b)

2.4 Weather variability

2.4.1 Temperature

It is necessary to consider forest planting season when selecting tree species to lessen potential effects of extreme events and where possible to counter damages altogether. Accordingly, for forest growth, the average values should be combined with short-term extreme weather variations in order to produce the factual data which are likely imminent to a study that can assess the relationship effect. An extraordinary drastic frost may put some trees in an abiotic state. In the same way, unexpected hot days might stop the physiological process of some tree species in the boreal such as the drought that can occur for a few weeks and kill several trees. Thus, as for tree growth is concerned, weather patterns need to include the exceptional events that have occurred to capture their effects on the actual value of forest growth.

Basically, during a period of modest warm weather condition, the boreal forest growth rate tends to increase, whereas the scorching sun has adverse effects on forest productivity (Eriksson & Vesterberg 2016). This study tests the same hypothesis by analysing the effects of the average temperatures on the growth rate of the forest for an extended period. The Scandinavian region has likely experienced global warming since an upward shift in temperature can be perceived. These patterns of weather illustrate evidence about the speed at which glaciers are retreating over time while temporal scorching days have been recorded repeatedly during the summers.

2.4.2 Precipitation

On the other hand, the average amount of precipitation corresponds to the rain expected to fall on different occasions annually. Forests grow better in moist areas with easy access to enough water. Based on practical experience, forest ecologists came up with a rule of thumb that forests rarely grow in dry geographical locations where the average rainfall gets lower than about 700 millimeters (mm) annually.

Nonetheless, this may rely relatively upon the amount of rain that falls periodically associated with its level of evaporation as well as the readiness of soil to save this water since enough soil water storage implies essential effects in the growth of forests (Landsberg & Waring 2014).

In Sweden, the average amount of rainfall per year reaches between 500 and 800 mm, which characterizes a dry geo-climatic zone compared to the world average annual rainfall.

2.4.3 The length of the vegetation period

The span of the vegetation period is also called as the growing season in the forest sector. According to the Swedish Meteorological and Hydrological Institute (SMHI), the length of vegetation period starts the first day in the year when the daily average temperature is at least +5 degrees for at least four days. This period ends the last day in the year when the daily average temperature is at least +5 degree for at least four days. The length of the vegetation period is the number of days from start to end, including the start and the end days.

Unfortunately, during a particular year, temperature variation can largely exceed the average temperature values causing difficulties to determine the precise point in time of which the average daily heat overreaches a homogeneity value. For instance, the average temperature from day to day over ten years has provided consistent temperature variability in southern Sweden, more specifically in Götaland and southern Svealand. Unlike the extent to which length of the vegetation period in the southern part of the country has been increasing, the length of the vegetation period in northern Sweden is estimated to increase about 14 days in the past 40 years with a rapid rise recorded in the last decade (smhi.se 2019).
The length of the vegetation period is expected to be very long by the similar number of days in spring and in autumn with the more prominent variation to be observed in the South, and weaker changes to be recorded in the North of Sweden.

2.4.4 Windstorms

The most anticipated extreme weather events are storms which unpredictably affect Swedish forests. See, for example, the winter storm Gudrun that hit the country in 2005 (Haanpää *et al.2005*). At the same magnitude or more severe windstorms, the risk of wind-felling of the forest will always be higher due to weather conditions and seasonal soil properties.
The primary driver of forest damages is wind speed. The critical limit of average wind speed to cause significant adverse effects on the forest is set to be about 15 m/s and blasts of about 30 m/s (Kellomäki et al., 2005).In Sweden, surprisingly the blasts of Gudrun storm reached more than 40 m/s on the west coast and almost the same speed in the central parts of the country.

More importantly, different studies found that the dominating planted Norway spruce was much more vulnerable to storm winds, particularly with massive falling trees of between 30-40 years of age (e.g., Alexandersson *et al.* 2005)

Also, several other factors affect the robustness of forests. The prime factors are the thinning and harvesting methods since a recently and heavily thinned forest stand will be damaged easily by a wind storm (Kellomäki et al., 2005). In the last ten decades, the area of forest plantations has increased substantially, and the earliest tree stands as well as grasslands have become less steady in soils. On top of that, the current massive heavy harvesting equipment put undoubtedly the value of toppling timber at high risk (Alexandersson, *et al.* 2005). Therefore, indeed, human activities have also increased the risk of severe impacts significantly due to storm events towards forest stands.

3 Literature review

Effects of intensive silvicultural practices and weather patterns on Swedish forests are expected to be tremendous. The complex variability of weather conditions may generate positive as well as negative effects on forest growth over an extended period and in different geographical locations. Therefore, in the broad interests of forest industry profitability, applying intensive forest management systems needs to minimize the risk of adverse effects and maximize the benefits of weather variations.

In Sweden, forest growth has been at an increasingly higher rate compared to the annual forest harvesting volume over the last 100 years. Furthermore, the effects of intensive silvicultural methods to increase forest standing volume have contributed importantly to a more massive potential increase of timber harvest as well as to increased carbon sequestration provided by the forest ecosystems (SFA 2015). For example, the results from the empirical study suggest that forest management systems with the purpose to increase biomass productivity in the boreal zones would contribute to a reduction of further carbon emissions by about 40 million tons of CO2 emissions annually (Lundmark *et al.* 2014). The present study further tests this hypothesis by introducing silvicultural treatments and weather variability as determinants of growth rates in Swedish forests.

3.1 Management practices and forest growth

The optimal forest management practices that determine the level of carbon sequestration are relatively dubious in the long run. Many studies suggest that the optimal rotation period for clear-cutting forest stands and planting new seedlings lead to a more substantial gain of carbon storage in the context of wood bioenergy production because an increase of forest biomass is more likely in young forests (Sedjo & Tian 2012). However, there are other secondary drivers such as global warming that may affect forests to react as net emitters rather than carbon emissions sinkers which could shorten the optimal rotation period of forest stands (Bellassen & Luyssaert 2014).

Low availability of mineral fertilization in boreal regions is a limiting factor on the growth rate (Högberg *et al.* 2017). Several studies confirmed that fertilization added nutrients that have a tremendous impact on tree growth (Fox *et al.* 2007; Saarsalmi *et al.* 2014; Noormets *et al.* 2015). Additionally, it is recommended to fertilize the later forest stands rotation because this fertilization timing leads to the productivity of high-quality timber rather than improving the branches of the butt log before clear felling (Tapio 2013). Also, when mineral soils of the boreal zone suffer a lack of nutrients, the critical recommendation is fertilizing (Saarsalmi & Tamminen 2005).

Many series of experiments focused chiefly on the fertilization effects for the present rotation period, but it turns out that these effects exist until the next period. For instance, a large quantity of pre-harvest fertilizers has adverse effects on soil chemistry after final harvest (Ring 2004). Some contradicting empirical results which found positive effects are, however, also reported (Johansson *et al.* 2013b). Similarly, another experimental study that estimated the long-term effects of fertilization regimes found the growth of stem-wood increments to be significant with intensive fertilization. The growth response relationship was, however, relatively robust in the less intensity fertilization regimes (Jacobson & Pettersson 2010).

Based on modern technologies, experimental studies were carried out to understand the apparent effects of thinning on both dominating tree species in Sweden, Norway spruces, and Scots pine. Some of the tested hypotheses were to examine whether management treatments that associated thinning with use of fertilizers could have beneficial effects on forest growth and yield. More profoundly, these studies intended to understand the underlying effects on tree volume growth, the stability of forest stands, and the quality of woods under separate thinning periods at different intensity (Eriksson 2006). The results are exciting but also conflicting. He found that management practices that intended to maximize biomass production could, in turn, have adverse effects on maximizing carbon sequestration. The study results asserted that thinning regimes for spruce stands have no significant effects on mean annual increment, and fertilizers alone also show no positive effects on biomass production when applied from above-ground. Accordingly, combining thinning and fertilization in the pine blocks showed significant results with an increase in the mean annual increment for biofuel production.

He concluded that when the objective is to maximize the biomass productivity, the enormous standing volume for both species is observed under the unthinned regime and thereby increasing carbon storage.

Scarification practices improve the planted seedlings' growth as an effect of the changes in the environment, such as the availability of nutrients and soil compositions, i.e., temperature (Johansson *et al.* 2006). The great prospect of scarification is to eliminate competing vegetation, which in turn more facilitates newly planted seedlings to grow under favourable conditions than woody and other herbaceous species of which can typically dominate the area after harvesting (Thiffault *et al.* 2005). Several other studies have found that scarification contributes positively over time. For example, scarification enhances forest stand to be homogenous and preserves the initial gains for planted seedlings for a very long time (Nilsson & Allen 2003; Johansson *et al.* 2013b). Accordingly, scarification is not only carried out primarily to promote seedlings growth but also to protect these seedlings against diseases such as pine weevils (Hylovius abietis) (Nordlander *et al.* 2011). Therefore, the importance of scarification in reducing the pine weevil attacks will likely be significant in the future because the current forest protection forbids the use of insecticides.

In recent years, scarification has gained much interest due to technological progress in the forest sector in Sweden (Johansson *et al.* 2013a). A limited number of studies have asserted a positive relationship between forest productivity and intensive scarification for better management of forests (Mattsson & Bergsten, 2003; Nordborg *et al.* 2006). As a result, the corresponding scarification cost could make the entire forest project more expensive during pre-commercial thinning even though it raises tree biomass increment. Conversely, some of its long-term effects could lead to much more resource nutrients, which in return contribute undoubtedly to the non-declining height as well as the basal area of young planted trees. For instance, (Johansson *et al.* 2013a) found that there was a remarkable difference in tree heights over the first 14 years between forest stands with scarification treatments and non-treatment stands. After then, trees follow a constant growth rate from 14 to 18 years of age of which the difference from both standing trees maintained uninterruptedly, and growth curves stopped to diverge. It turned out that forest sites located farthest North indicated a vast difference in growth heights which could reach up to 11 years, and this incredible time difference represents the enormous effect on the economy of the forestry industry.

3.2 Weather patterns and forest growth

A study that assessed the effects of climate variability on the function and structure of boreal coniferous forests found that an increase in temperature could enhance forest function substantially (Kellomäki & Väisänen 1997). The results show tremendous effects on forest growth when the temperature is associated with an elevation of carbon from above-ground. They reported that forest growth increases at lower levels than expected because of the higher resistance of trees during elevated temperature. However, this result follows the underlying assumption that respiration during dark periods is lowered to no considerable extent by elevation of CO2 concentration.

The boreal coniferous forests are susceptible to high temperature. Using the process-based simulation model to estimate and compare the effect of elevated temperature and CO2 concentration on net primary production (NPP) in the Nordic countries (Bergh *et al.* 2003)), they found an increase of about 24-37% of NPP in spring for Scots pine and Norway spruce. However, beech stands did not respond conveniently with the increase in temperature of spring to the same extent as the other deciduous species. In Denmark, for example, the effect of elevated CO2 concentration was more observed for the beech stands. The high CO2 concentration helps the efficient use of water in stands with water deficit.

Different reasons can explain a positive relationship between average temperatures and the growth in October of the previous year. Higher October temperatures are likely to contribute to the extension period of physiological function until the end of the growing season. Thus, allowing exhausting relocation of transportable nutrients from leaves to seasonal living parts of the trees during the prolonged time. For instance, (Barbaroux & Breda 2002) reported that timber maximizes the reserves storage in October. Besides, a similar study of red oak (Q. rubra L.) revealed the maximum sugars relocated to the main stem existed in late October (Xu & Griffin 2006). Therefore, October reveals warmer weather conditions which determine the amount of the carbohydrates transferred to perennial parts of the tree and thus producing more available nutrients and energy reserves for the next growing season.

On the other hand, the damage of severe windstorms had significantly increased both in frequency and magnitude during the later 20th century (Munich Re 2002).

There are several other instruments such as changes in stand age and structure, and forestry management treatments that also vary over time, consequently reshaping windstorms sensitivity to forests. An analysis of the panel data on windstorm damage in Sweden during 1901-2000 Nilsson *et al.* (2004) found that storm damage to forest frequently manifested at the age of 51 years. An empirical assumption is that thinning forest stands will need to be done at the age of 41 years and that the stand height is significant enough to imply being exposed to the risk of windthrow (Persson, 1975). During that period, the study estimated 77 different windstorms and a total volume loss of about 110.7 million m^3 (Nilsson *et al.* 2004). It appears that the terrible storm damage was observed more in the south than in the north of Sweden. The results also indicate that the increase in storm damages in the entire country over the last century was likely due to the relatively larger forest proportion in the landscape and absolute volume associated with the age classes inclined to storm damage, not because of storm frequency and its magnitude (Nilsson *et al.* 2004). Also, the changes in management practices may be another substantial cause.

3.3 Carbon Sequestration

The age of the forest is one of the first measurements that help to quantify the amount of carbon sequestration. The growth of tree biomass rises rapidly in the early stage of plantation following a non-linear growth rate, unlike the flowing of carbon that has mainly been estimated using linear functions without considering forest age. As a result, the studies that included the age of forest while estimating non-linear tree growth function noted minor carbon emissions sink (Brainard *et al.* 2009). More economic factors and biological properties of forests are needed to predict accurate results. Like in most other countries, there is no recent market valuation of carbon sequestration in Sweden (Gren & Aklilu 2016; Gren & Amuakwa-Mensah 2018). Estimating the unit of the carbon sequestration needs to compare the related costs of reaching climate neutrality through the reduction of carbon emissions and any other greenhouse gases (GHG). In this study, the current tax scheme on carbon emissions is used to determine the value of carbon sequestration as the societal willingness to reduce GHG emissions. For example, in a thorough study conducted in the Swedish forests (SEPA 2012), it was found that the annual carbon emissions sink could reach up to 38 million tonnes of CO2 emissions per year. Forests with the ability to grow further are the net saver of CO2 emissions and forest management practices have vital effects on carbon sequestration at a larger scale.

4 Methodology and empirical data

This section illustrates the methodology of fully modified ordinary least square (FMOLS), and the empirical work of creating an estimation of the total economic value (TEV) of the forest ecosystem services of timber and carbon sequestration. Also, this includes describing unit net prices that were used in this model.

4.1 Methodology

Two main steps are conducted to produce the total economic value of forest ecosystem services focusing mostly on the value of timber and carbon sequestration. The starting point is a step (i) which examines effects of weather patterns and management systems on forest growth, and next step (ii) is the estimation of the total economic value of timber production and carbon sequestration.

In forestry, non-linear growth functions are mostly preferred compared to linear modeling since the linear functions often fail to deliver according to the educated guesses (Wang 2006). However, Hastie & Tibshirani (1986) and Wood (2017) suggested that using additive models' approach is essential because it handles complex relationships between the explanatory variables and the response. The recommendation from economic literature is that step (i), of estimating the effects of weather variability and forest management practices on forest productivity, is regarded as estimating the growth function. It utilizes an underlying assumption that the growth function follows a sigmoid shape from the starting point (0,0) which is then followed by inflection point that appears at the beginning of the adolescent stage, and reaches the peaks and then falls in the maturity stage (Fekedulegn *et al.* 1999).

The non-linear relationships with their rigorous mathematical attributes pass the fitness test by providing meaningful feedback about the rate of growth, the inflection point, the initial forest stands, and the maximum yield. Nonetheless, there is a high correlation of the parameters in non-linear functions because a change in one estimated parameter induces changes in other parameters to keep its original functional form. On the other hand, using the adding-up approach, Amuakwa-Mensah *et al.* (2016) concluded that explanatory variables could lead to a wrong conclusion about the relationship between these variables and the response.

Therefore, this study selects the logistic function in the form of a linear transformation because it is more pertinent for estimating the parameters of the model than using other non-linear growth functions such as Von Bertalanffy, and Schnute (Fekedulegn *et al.* 1999). Besides that, the linearized growth function has illustrated to providing more accurate predictions (Nguimkeu 2014). Accordingly, this growth model usually tends to be a beneficial instrument for studying the tendencies of different population growth Nguimkeu & Rekkas (2011) such as the forest in applied research.

Given that this thesis opts to use a linearized logistic function with no intercept, it allows equation (1) to be expressed as follows;

$$y_{t+1} = y_t\left(1 + \beta_1\left(1 - \frac{y_t}{\beta_2}\right)\right) - H_t + \beta_3 X_t + \beta_4 W_t \qquad (1)$$

It is expressing the increase in the volume of forest growth per hectare during year (y_{t+1}) as a function of forest volume in the previous year (y_t), the harvest of timber (H_t), a vector of intensive management practices (X_t) and weather variability (W_t). A linear logistic function expressed in terms of intrinsic growth rate, β_1, and maximum productivity, β_2 helps to estimate impacts of a marginal change in management and weather on the forest growth. Moving the annual harvest (H_t) to the left-hand side will minimize the problem of multicollinearity between volume harvest and a set of management treatments. By dividing both sides by the standing volume per unit area (y_{it}) and keeping the (W_t) aside off the equation (1) is transformed into equation (2).

$$\dot{Y} = \beta_1\left(1 - \frac{y_t}{\beta_2}\right) + \beta_3 \frac{X_t}{y_t} \qquad (2)$$

Where $\dot{Y} = \frac{y_{t+1} - y_t + H_t}{y_t}$ represents 'adjusted growth rate'. (3)

The adjusted growth rate is the value of the growth of forest productivity. With direct effects of intensive management practices involving thinning, scarification and fertilization and weather variability which includes variations in temperature, precipitation, length of the vegetation periods and windstorms, I expect the intrinsic growth rate, not least β_1 to be positive but it is arduous predicting the impact of weather variability, not least the sign of β4.

The marginal impact of intensive silvicultural systems on the forest growth rate may also be ambiguous, not least the sign of β3. While estimating the impact of weather patterns and silvicultural practices, the response variable is narrowed to the rate of growth in forest productivity over the years, equation (3).

The statistical results on the data used in the econometric analysis are presented in table 1.

Table 1. Descriptive statistics

Variables	N	Mean	Std. Dev	min	max
$\dot{Y}_t$: *Adjusted growth rate*[a]	195	0.0368	0.0670	-0.3721	0.5069
H_t: *Harvest, m*^{3}*/ha*	196	2.5645	1.3694	0.4849	7.8676
y_t: *Standing volume, m*^{3}*/ha*	196	93.8149	32.0559	29.3409	163.7074
Scarification, % of productive area	196	0.00625	0.0019	0.0174	0.0114
Thinning, % of productive area	196	0.01278	0.0045	0.0056	0.0277
Fertilization, % of productive area	196	0.0035	0.0031	0	0.0132
Fertilization policy	193	0.1011	0.1703	0	0.8847
Temperature, degree Celsius	196	0.4210	1.0217	-2.05	2.3
Precipitation, mm	196	4.9948	14.911	-29	47.6
Windstorm, m/s	196	2.376	1.1577	0.48	6.32
Length of the vegetation period, number of days.	196	4.2925	7.6048	-11.78	26.62

[a] $\dot{Y}_t = \frac{y_{t+1} - y_t + H_t}{y_t}$, the adjusted growth rate.

Also, introducing the indirect effects of weather patterns and management practices as explanatory variables on the intrinsic growth rate following the (Amuakwa-Mensah *et al.2016*; Gren *et al.* 2016) gives the equation (4)

$$\dot{Y}_t = (\theta_{i1} + \theta_{i2}X_{it} + \theta_{i3}W_{it})\left(1 - \frac{y_{it}}{\beta_{i2}}\right) \tag{4}$$

where $\beta_{it1} = \theta_{i1} + \theta_{i2}X_{it} + \theta_{i3}W_{it}$. This regression function corresponds to equation (5)

$$\dot{Y}_t = \rho_{i1} + \rho_{i2}y_{it} + \rho_{i3}X_{it} + \rho_{i4}W_{it} + \varepsilon_{it} \tag{5}$$

$\rho_{i1} = \theta_{i1}$, and $\rho_{i2} = -\frac{\beta_{i1}}{\beta_{i2}}$. Now the intrinsic growth rate has changed to time dependent and $\beta_{it2} = \rho_{i1} + \rho_{i3}X_{it} + \rho_{i4}W_{it}$.

The rest of the parameters are like the ones in the direct model. However, this study does not analysis the results of the indirect approach.

Finally, in step (ii) changes in forest productivity affect the total economic value through timber harvesting and carbon sequestration.
Quantification of the monetary value using the unit net income from timber and carbon sequestration, P^T and P^{CO2} respectively, implies that the total monetary benefits that society gains from the two provision types of forest ecosystems is determined in the equation (6).

$$TEV = P^T * H_t + P^{CO2}Conv(y_{(t+1)} - y_t) \quad (6)$$

P^T is the price per cubic meter, H_t is the volume harvested in cubic meter (m^3) and *conv* is the conversion of change in forest volume to carbon dioxide equivalents (CO_2e) and needs to be calculated.

The fully modified ordinary least squares (FMOLS) approach (Wang & Wu 2012) is used in this study to estimate the type of equation (6). It follows that the fully modified OLS as proposed by Phillips & Hansen (1990) tends to be a half parametric model and is robust to endogeneity, though with the presence of serial correlation problems. Furthermore, FMOLS produces coherent and adequate estimations for the model lacking cointegration relationship and implies outstanding robustness for both stationary and non-stationary series in the same cointegration analysis. Since a long panel data is used for the analysis of this thesis, FMOLS becomes very handy to avoid problems related to serial correlation and non-stationarity. Using Stata, the system starts by modifying variables and is followed directly by discarding the existing undesirable parameters. The FMOLS is structured in a way that allows for correcting endogeneity and serial correlation problems using an adequate approach in the sense that it maintains the original functional form of the linearized logistic function.

4.2 Empirical data .

This thesis uses panel data to estimate the forest productivity as described in chapter 4.1, on four regions of Sweden for the period 1965-2013. The data on forest related indicators is provided from the Swedish Forestry Agency 2014 and weather conditions are obtained from the Swedish Meteorological and Hydrological Institute (SMHI) 2017. "The materials cover all statistics during the entire study period, and they are deviations from the annual average values for forest management practices and weighted yearly average values for weather variability."

Measurements of scarification, thinning and fertilization are in terms of percentage of forest productive areas and the indicator of harvest is in cubic meter per hectare. The total average standing volume in all regions of Sweden amounts approximately 120 m^3/ha, and the southern parts comprise the highest standing volume, whereas the northern parts aggregate the lowest volume. The total standing volume was 3 billion cubic meters of productive forest land area (Christiansen & Fong Ekistrand 2013). The four different forest zones have different climate conditions (fig. A1). The northern regions comprise of Norra and Södra Norrlands and are the largest zones with more significant forest area compared to the southern regions, not least Svealand and Götaland. The larger part of Swedish forest is the boreal coniferous forest with only two dominating tree species, Scots pine (Pinus sylvestris) and Norwegian spruce (Picea abies) in the entire country totalizing between 76% and 84% of standing volume in productive forest area (Christiansen & Fong Ekistrand 2014). The rest of tree species which mostly are broad-leaved trees are found mainly in the southern region. Birch (Betula spp.) takes about 10-15% of the total standing volume, and beech (Fagus spp.) and oak (Quercus spp.) both combined comprise nearly 6% of the total standing volume and most are in Götaland. The standing volume measured in m^3/ha differs in all four forest regions (Amuakwa-Mensah *et al.2016)* . The standing volume in Götaland almost doubles the standing volume in Norra Norrland. Several reports have found that there has been a steady increase in standing volume per hectare in a productive forest area during the same period (Amuakwa-Mensah *et al. 2016*; Christiansen & Fong Ekistrand 2014).

In 1985 a policy of regulating fertilizers was introduced in the forestry sector due to the eutrophication problem of coastal waters in Sweden. This problem is linked to the overload of nutrients which lead to damaging the bottom sea areas then creating an increased frequency of toxic blue algae while also changing fisheries composition at the cost of commercial species (Conley *et al.* 2009). These sorts of damages hit Götaland severely, and therefore, authorities imposed stricter regulations in this region than in the other parts of Sweden. Since then, data collection was also changed in the same year as the introduction of fertilization policy. This empirical study introduces a dummy value which takes a value of 1 from 1985 onwards and 0 otherwise with the purpose to maintain impacts of the fertilization policy and change in data collection on the growth rate.

On the other hand, this study uses the weighted average values of the maximum and minimum temperatures while considering the temperature at given moments in all four different regions.

The observations provide an almost correct, and accurate yearly weighted average temperature that follows the international rules. They are calculated based on the average temperature of the twelve rounded monthly average values rather than the daily average values, which are recorded every three hours a day on the Celsius scale (smhi.se 2018). Also, the annual weighted average temperature is rounded to one decimal of degree Celsius. Similarly, windstorm, which is known to be the natural event, is measured in meters per second using the annual weighted mean value of the wind following the principle of the average wind values recorded for every ten minutes in Sweden (smhi.se).

Precipitation in Sweden is one of the vital meteorological parameters, which is measured in millimetres (mm). This research uses the yearly weighted average values of the rainfall. The precipitation provides a 1 mm thick layer on a horizontal surface with no presence of actual evaporation and water flowing away. However, deviations from the mean values of precipitation do not take into account the amount of moisture and hoarfrost as in other parts of the world. Differently, the length of the vegetation period with a daily mean temperature exceeding a certain threshold indicates the time of the year for the tree to grow and is usually measured in terms of a period of time such as days or weeks (smhi.se 2019). Since the starting of this growing season chiefly relies on the air changing temperatures, and other combing factors ambiguously explain the end of the season such as prolonged daylight time, conditions of moisture, utmost temperatures, extreme frost occurrence, etc may also explain the minimum value of the length of the vegetation period to have a negative sign as indicated in the table of description (table 1).

The underlying assumption that forest owners are rational and they should optimize the value of timber to be harvested in each period, H_t, based on the market prices and forest growth (e.g., (Sohngen & Mendelsohn 2003). A further assumption is that carbon sequestration is part and parcel of harvesting decision. Therefore, forest carbon sequestration uses the existing payment model to reduce the emissions of greenhouse gases (GHG). There are several studies on estimating the forest carbon sequestration and the impacts of management systems (Janssens *et al.* 2005; Helin *et al.* 2013; Lundmark *et al.* 2014). This study evaluates carbon located in the aboveground biomass and ignores carbon found in soil. However, the total felling and wood made materials cause the release of carbon from aboveground. Considering the explained patterns, a study that estimated the net carbon sequestration in the Swedish forests concluded that the averaged value had reached 0.47 ton CO_2e/m^3 harvest (Lundmark *et al.* 2014).

The present study, however, does not consider the same approach since there is a lack of data on carbon sequestration from the growth rate. Instead, it is calculated. The use of the conversion for felling, which means less carbon sequestration per hectare because of the average growth rate in standing volume is higher compared to the average harvest.

5 Results analysis

The four forest zones provided information that was useful in forming a panel data to be used for estimating the impact of management and weather on forest productivity for the entire country. In this study, the panel data gives adequate observations with no further adjustments to get the accuracy and efficiency of the regression estimates. Furthermore, introducing zonal fixed effect helps to characterize each zone with unique features because these specific features may affect the response variable.

Thus, having presented data in the previous chapters and based on the econometric models, the results are analyzed following the estimated forest productivity in association with total economic value computations. The use of logistic growth functions with parameter values which estimate the effect of management practices and weather patterns turn out to yield significant productivity. It was decided to test the effect of lagged and non-lagged variables of these practices and weather variability because of delays in the effect of both explanatory variables. As such, the results indicated that the lagged variables produce a better fit of statistical significance compared to the findings from non-lagged model. Thus, all regression estimates in this study consider the lagged variables. See the results of the logistic functions, as presented in table 2.

Table 2: Regression results from fully modified ordinary least square (FMOLS) of the growth rate of Swedish forest productivity (Standard errors in brackets).

VARIABLES	Direct Model	Indirect Model
Constant	0.1012***	0.1307***
	(0.0168)	(0.0133)
Standing per hectare	-2.9421***	-2.7124***
	(0.3349)	(0.3276)
Fertilizer (_1)[g]	0.0660	-1.9036
	(0.0926)	(1.4252)
Fertilization policy (_1)[g]	0.0001	0.0322
	(0.0016)	(0.0231)
Thinning (_1)[g]	-0.0694	-0.0482
	(0.0501)	(0.6605)
Scarification (_1)[g]	0.3906***	2.3375
	(0.1186)	(1.4911)
Temperature (_1)[g]	0.0079***	0.0079***
	(0.0020)	(0.0021)
Södra Norrland	0.0383***	0.0357**
	(0.0146)	(0.0140)
Svealand	0.0077	0.0177
	(0.0286)	(0.0281)
Götaland	0.0234	0.0411
	(0.0403)	(0.0399)
Trend	0.0017***	0.0012***
	(0.0004)	(0.0004)
Precipitation (_1)[g]	0.0001	0.0001
	(0.0001)	(0.0001)
Length vegetation (_1)[g]	0.0011***	0.0009***
	(0.0003)	(0.0003)
Windstorm (_1)[g]	0.0010	0.0009
	(0.0016)	(0.0016)
Observations	187	187
R^2	0.0526	0.0718
Long Run SE	0.0248	0.0247
Bandwidth(neweywest)	65.02	67.40

[g] One-period lag.
Significance level: *** p<0.01, ** p<0.05, * p<0.1

The direct and the indirect regression models with the management of scarification and weather patterns of temperature and the length of the vegetation period indicate to have a better fit of statistical significance. Both models retain small and almost equal long-run standard errors, which is 0.0248 for the direct model and 0.0247 for the indirect model. The analysis of this study chooses to use the direct model because it provides straight forward results and easy to interpret.

These growth models generate the constant of intrinsic growth rate β_1, which is significant in both the direct and the indirect models, with the estimates of 0.10 and 0.13, respectively. The estimated constant growth rate of this study is closer to the amount of 0.13 found in the direct model of the assessment of the impacts of site quality on growth rate and variability of forest productivity in Sweden Amuakwa-Mensah *et al. (2018*). Additionally, this intrinsic growth rate is convenient to the range of the estimate of 0.11 reported in the boreal forest at large scale (Eriksson & Vesterberg 2016). Also, the standing volume retains the negative sign as expected, and it is reported to be -2.94, and it is closer to the estimate of -2.10 found in the study of the effects of the site quality on the growth rate in Sweden *Amuakwa-Mensah et al.* (2018). In other words, the growth rate in forest productivity is reported to be at a low level with high productivity degree. The indicator signaling variations in standing volume per hectare productive area over time, the variable of the trend, for the period 1965-2013 is recorded to be positive and significant. The regression equation reported the trend to be 0.0017 and 0.0012 in the direct and indirect model, respectively, which means that all four forest regions experienced a steady increase in standing volume.

5.1 Management practices and forest productivity.

The regression results pass the fitness test while assessing the effects of management practices on forest productivity. It turned out that scarification is the only management treatment which has a significant effect on productivity, whereas thinning and fertilization practices have no significant effects on forest growth. Scarification is the most pertaining practice to enhance environmental conditions which favor forest plantations in Sweden. With the direct model, the estimated impact of scarification is positive and equals 0.39. Which means that a one-unit increase in scarification contributes about 0.39 percentage point in forest productivity.

One important reason could be that this management treatment not only contributes significantly to the increment of the standing volume per ha but also at high levels of productivity. Thus, the growth rate increases with the best scarification practice and at the same time, which leads to lower mortality of planted trees. Scarification, therefore, would be expected to have a significant effect on the economic value of the forest stand. Another reason could be that the one-period lagged model of these management indicators succeeds in capturing only the long-term effect of scarification.

When considering the indirect impacts, there is no single management system which shows significant effect on the growth rate. The practices of fertilization and thinning are negative, and they reveal to have no significant effects on forest productivity. Conversely, scarification and fertilization policy are positive, but they also have no important effects on productivity. The reason might be that since these practices are positive, they may have significant effects on the growth of the standing volume per ha with a low degree at higher productivity. Which means that the growth rate increases as the magnitude of the management practices also increase. Furthermore, it could be that the one-period lag of these variables does not consider the long-term impacts of the management methods in the model.

5.2 Weather variability and forest productivity

Weather variability in boreal forests exhibits attributes on standing volume due to relatively annual growth, warmer temperatures, and the number of daily degrees. The findings of this study demonstrate that the changes in some weather patterns can have profound effects on forest ecosystem services in Sweden. Temperature and length of the vegetation period are both positive and significant at 1% level. Also, they reveal to have a considerable impact through the increase of the expected economic benefit of carbon sequestration with the estimates of 0.0079 and 0.0011, respectively. In the long run, one of the critical reasons could be that on average, high temperature induces the increase of the stem-wood growth of planted trees in cold regions (i.e., boreal zones). The temperature is vital for metabolic processes entailing storage of carbon, which is an essential factor to aboveground plant productivity. Therefore, the rise of temperature together with adequate precipitation and nutrients help in the accumulation of higher biomass.

Furthermore, one of the indirect impacts of warming is often the length of the vegetation period, also known as the growing season. The results show that the length of the growing season has increased over the past decades, and it has a positive effect on the forest growth rate and at the same time on the increase of carbon sequestrated. Unfortunately, these results cannot be compared to any other study since there has been hitherto no similar research.

Similarly, the factors of temperature and the length of the vegetation period in the indirect model have closer significant impacts on the forest growth, with the estimates of 0.0079 and 0.0009, respectively. On the other hand, patterns of precipitation and windstorm reveal to have no significant impacts on forest growth. Decreasing of summer precipitation may cause soil water shortages in Swedish forests, and these shortages could be due to the increase in temperatures. The indicator for precipitation shows no effect on forest productivity since it is estimated to be zero, 0.0001, while the estimate for windstorm is 0,0010, and both variables are not significant.

5.3 Estimation of the total economic value

All monetary values are expressed in SEK. The price of timber is SEK 455/m^3 for saw timber and SEK 284/m^3 for pulpwood. While the harvested volume used for saw timber and pulpwood reached nearly about 40% and 50% respectively (Nilsson *et al.* 2017), the remaining wood materials are most important for bioenergy, and there is no official data on prices because forest owners consume them locally (Carlsson 2012). Thus, this study uses the average price for timber, P^T, of SEK 360/m^3 (Gren & Amuakwa-Mensah 2018).

With regards to the unit price of carbon sequestration i.e., P^{CO2}, there is extensive body of literature that analyzes the marginal cost of carbon for society. They have reported to range from 50 and 2470 SEK/ton CO2e (a review (Tol 2013)). In the recent study that takes into account the risk of uncertainty, the value of carbon sink enhancement could reach up to 2540/ha (Gren & Amuakwa-Mensah, 2018). The cost of carbon on the European trading market could change continuously and range between 45 and 300 SEK/ton CO2e from 2007-2014 (MacDonald 2016).This thesis has considered the average carbon price of SEK 162 /ton CO2ev/m^3.

Furthermore, the conversion factor of forest biomass, *Conv* is 0.91 ton CO2e (Carbon dioxide equivalents) /m^3 harvest volume for coniferous and 1.47 ton CO2e/m^3 for deciduous forest (Vass & Elofsson 2016; Gren & Amuakwa-Mensah 2018). Since the conifer and deciduous forest cover areas are equivalent to 89% and 11% respectively. It appears that the conversion factor for average carbon sequestration is then conv=0.91*89%+1.47*11%=0.97-ton CO2e/m^3.

Having parameterized the growth rate, we can now estimate the values of timber and carbon sequestration based on the average values of parameters of interest. The total economic benefit of these ecosystems is calculated following equation (6) and the principles and data, as explained in previous sections of chapter 4. The calculation of the contribution of significant weather variability to the increase of monetary benefit gives the total economic value of forest ecosystems. At start, the total economic value is calculated for the base scenario, whereby no other consideration of variable changes. After that, temperature and the length of the vegetation period are introduced in the calculations since they appear to be significant for forest ecosystems studied.

Having $\frac{\Delta \dot{Y}_t}{\Delta\ temperature} = 0.0079$; the change in adjusted growth rate relative to the change in temperatures is constant and equals the coefficient value of temperatures. Therefore, $the\ new\ \dot{Y}_t = average\ \dot{Y}_t + \frac{\Delta \dot{Y}_t}{\Delta\ temperature}$; a one-unit increment of temperature will generate a new adjusted growth rate starting from the levels of average growth rate.

From equation (3), the newly adjusted growth rate amounts to $\frac{y_{(t+1)} - y_t + H_t}{y_t} = \dot{Y}_t + \frac{\Delta \dot{Y}_t}{\Delta\ temperature.}$; which gives the difference in variation of standing volumes in different periods. Thus, $y_{(t+1)} - y_t = y_t(\dot{Y}_t + 0.0079) - H_t$.

In the similar procedures, a one-unit change of length of the vegetation period will impact the growth rate as follows; $y_{(t+1)} - y_t = y_t(\dot{Y}_t + 0.0011) - H_t$. Replacing the equalities of differences of standing volumes per hectare in the equation (6) produces the table (3) and it shows the total economic benefits of timber and carbon sequestration in various scenarios.

This means that, $TEV_{Temp.} = P^T * H_t + P^{CO2}Conv\left[y_t\left(\dot{Y}_t + 0.0079\right) - H_t\right]$ is due to changes in temperature and $TEV_{LengthVeg.} = P^T * H_t + P^{CO2}Conv\left[y_t\left(\dot{Y}_t + 0.0011\right) - H_t\right]$ follows after the increase of the length of the vegetation period.

Table 3: Calculated total economic value and the average contribution of a one-unit increase of temperature and length of the vegetation period to the total economic value of timber and carbon sequestration in SEK/m3/ha.

		A one-unit increment of:	
	Base Scenario	Temperature	Length vegetation period
Timber:	923.22	923.22	923.22
Carbon Sequestration:	141.55	258.01	157.76
Total:	1 064.77	1 181.23	1 080.99

The results show that the expected economic benefit of the carbon sequestration augmented at different levels and the value of timber remained constant. These changes in carbon sink constitute the total impact of weather patterns on forest ecosystem services in Sweden. Furthermore, these variations are the same for all the regions under this study since the trend shows to have a positive and significant effect.

6 Discussion

The results indicate that the value of timber remains unchanged in all calculations and amounts to SEK 923 m^3/ha since the static model used in this study does not allow the significant temperature and the length of the vegetation period having effects on timber production. On the other hand, the model permits the same significant variables to have a considerable impact on the value of carbon sequestration. The expected benefits of carbon sequestration with a one-unit increase in temperature augmented to SEK 258/ton CO2e/m3 from the initial benefit of SEK 142/ton CO2e/m3. Moreover, with a one-unit increase of the length of the vegetation period, the value of carbon increases by 11.5%, which means that the value reaches SEK 158/ton CO2e/m^3. The total economic benefit in the base scenario is estimated to be SEK 1065 /m^3/ha. The rise of temperature and the length of the vegetation period increases the total economic value by 11 and 1.5 percent to attain SEK 1181 /m^3/ha and SEK 1081 /m^3/ha respectively compared to the base scenario. The increase is mainly due to the changes in carbon sequestration.

The calculation of the total expected monetary benefit of carbon sequestration in the whole country would be based on the estimation of total standing volume of productive forest land, which is reported to be 3 billion cubic meters (Christiansen & Fong Ekistrand 2014). However, since weather conditions are different across the regions, it cannot be easily possible to scale up the value of carbon sequestration at the national level (Amuakwa-Mensah 2019). On the other hand, following the unit price of timber as estimated in the table (3) the total economic benefit of timber production for the entire country equals 108.00 10^{10} SEK (see table A2). The results show that the economic benefit of this forest ecosystem is still constant and corresponds to 23% of the gross domestic product (GDP) in 2018. Reducing the value of timber production to 300 SEK/m3 its economic benefit drops to 19 % of the gross domestic product (GDP) in the same year. The comparison with the GDP is based on the data provided by (World Bank 2019) and the exchange rate of December 2018 (*Riksbank. Statistics* 2019). (See table A3)

The calculated economic values rely heavily on the prevailing assumptions of the price of timber and carbon sequestration. The values of the parameters used in the evaluation of table (3) rest unchanged. The average price of timber is 360 SEK/ m^3 during the period of the study.

The reference estimate of the carbon emissions tax is the average of the carbon price and amounted 162 SEK/ton CO2e/m^3. Also, the conversion for average carbon sequestration is estimated to be 0.97-ton CO2e/m^3 (ibid).

Therefore, the contribution to the total economic value from an increase of one unit for each of the unique variable of interest shows that the most significant effect occurs when there is a change in the price of carbon sequestration. Further crucial changes arise following variations in the price of timber and conversion factor. For example, considering the carbon price to be the same as the European carbon market price of 300 SEK/ ton CO2ev (table A1). The total economic values increase by 11% in the base scenario, by 18.5% for an average contribution of a one-unit increase in temperatures and by 12% for an average contribution of a one-unit increase in length vegetation period compared to their respective initial benefit values. Similarly, the value of carbon sequestration rises remarkably to almost double the initial carbon value in the three different scenarios with an increase of 85% extra benefit.

For the minimum price of timber to be 300 SEK m3/ha, the timber value reduces by about 17% of its initial value. Besides that, the total economic benefit changes downwards by 14.5% in the base scenario, by 13% with an increment of the marginal unit of temperature and by a reduction of 14 % with an increase of marginal unit of length of the vegetation period relative to their initial benefit values. Halving the value of the conversion factor to 0.48, the value of carbon sequestration is also halved to attain 50% of its primary economic value.

These results depend heavily on the underlying assumptions of prices of the forest ecosystem services of this study and the use of simple sigmoid growth function. Notably, this growth function ignores the composition of tree ages, the unchanged intrinsic growth rate, and the relative interconnectivity between volume growth and pressure intensity (e.g., Clark 2010). Using other growth functions, such as age-structured models could produce different predictions of forest growth since the Swedish forests are even-aged, and the age structure in a particular area has a tremendous impact on the forest growth. Also, more variables of interest need to be included in order to estimate such a function at the national scale. Despite that, the estimates of intrinsic forest growth rate for Sweden in this study are closer to the results found in other studies, such as Amuakwa-Mensah *et al.* (2018) and Eriksson & Vesterberg (2016).

Another critical assumption in this study is the conditional-response in forest management treatments if the introduction of compensation policy for carbon sequestration in Sweden is expected in comparison to some other countries (Gren & Aklilu 2016; Gren & Amuakwa-Mensah 2018). To simplify, timber, as well as carbon sequestration, have been associated with harvest. Of course, carbon sequestration is more complicated and depends on biomass growth, tree species, and soil conditions to mention a few. Therefore, introducing payments for ecosystem services such as carbon sequestration would likely result in changing management treatments and harvesting practices with the purpose to optimize the long term benefits of forest ecosystems of both timber and carbon sequestration (Gren & Aklilu 2016). Admittedly, these changes can be expected to increase the total economic benefit for the forests.

These present results illustrate a clear implication on the national forest policy. The policy aims to increase timber productivity equally the same as protecting biodiversity. With the use of the adjusted growth model, the results show that the value of timber remains constant with a one-unit increase of temperature and length vegetation period, whereas the value of carbon sequestration increases following the increases of the marginal increase in temperature and length of the vegetation period. The main explanation for these results to differ partly from the objectives of the policy is that the policy relies on the optimal management practices and the regression results have shown that scarification is the only management treatment which has significant effects on the forest growth. Furthermore, the increase in the value of carbon storage partly follows the long run harvesting decision under the present estimation method.

7 Conclusions

With the aim of this study, the findings illustrate that temperature and length of vegetation period are critical determinants of the economic value of carbon sequestration, which is one of the Swedish forest ecosystems studied. The use of the adjusted growth model could not verify the contribution of similar significant weather variability on the value of timber. It turns out that these variables of interest have long-term effects on boreal forest growth and therefore increase forest productivity through carbon sequestration. The value of timber and carbon sequestration from Swedish forests indicate that the average contribution from a one-unit increase in temperature amounts to SEK 1181/m^3 of the total economic benefits which correspond to 11% increase of the total initial value with an estimate of SEK 1065/m^3. On the other hand, the contribution from a one-unit increase of the length of the vegetation period amounted SEK 1081/m^3, which corresponds to an increase of 1.5% from the primary total benefit value in the base scenario.

The results show that the economic value of timber production in the entire country is equivalent to 23% of the gross domestic product in the year 2018. Unfortunately, the study could not compute the overall total economic value at the national level because of the nature of the weather conditions which vary across different regions in the country. The total economic value depends relatively to the assumptions on the prices and the value of the conversion factor.

These results are valid only for similar boreal conditions, but the methodological approach can be applied commonly to any other national scale where the average parameters' values of forest ecosystems are of paramount concern. Also, the positive of marginal effects on the adjusted growth rate imply that they are essential factors for optimal management activities relating to timber production and harvest practices. One area of interesting future research could be the optimization of management decisions that would allow long-term impacts on sustainable forest ecosystems. More explicitly, the use of quantitative interactions can help forests to provide a full range of potential economic benefits.

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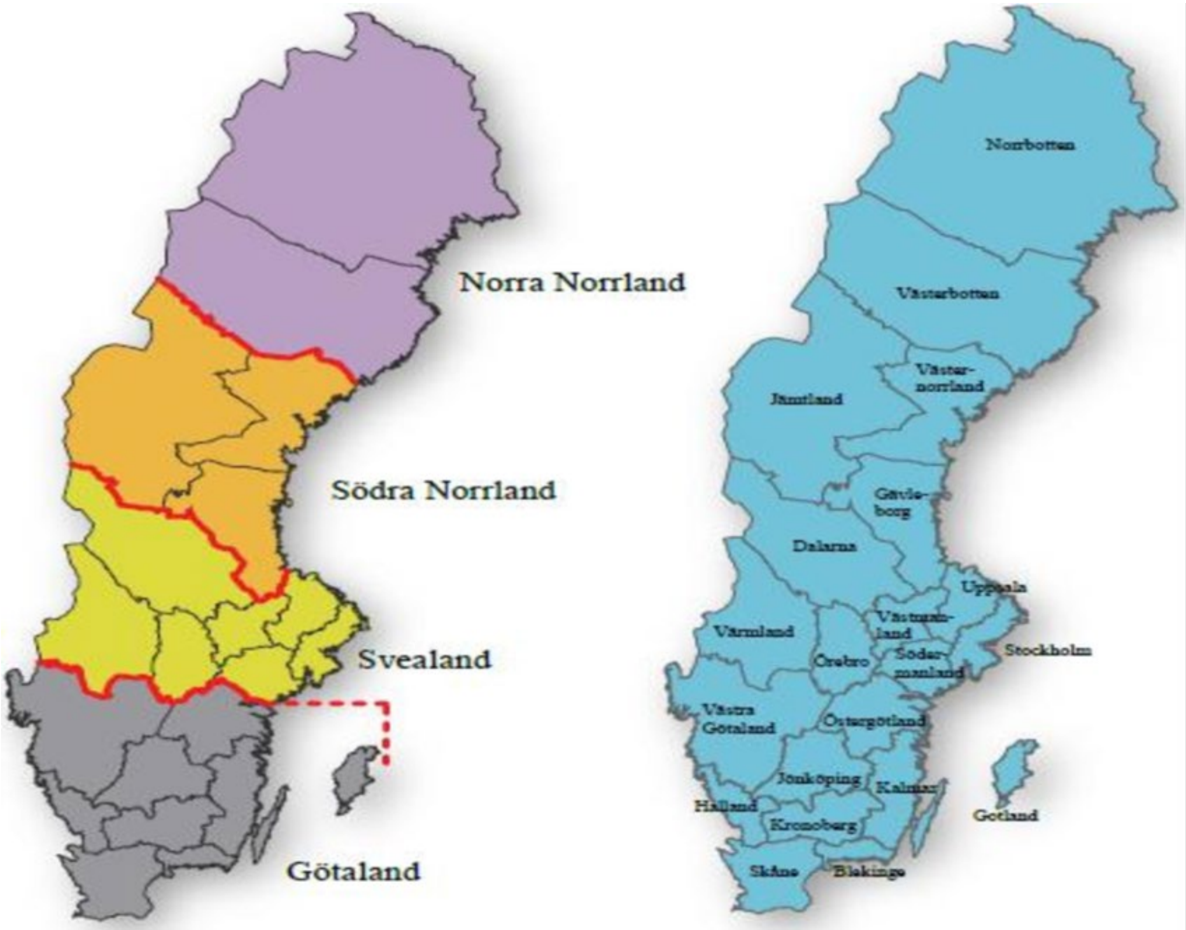
Appendix

Figure A1: Forest zones and counties in Sweden



Source: Swedish Forest Data, 2014 report. SLU, Forest Resources Management Department
NB: Norra Norrland and Södra Norrland are North Norrland and South Norrland, respectively

Table A1: Calculated total economic value and average contribution of a one-unit increase of temperature and length vegetation period to the total economic value of timber and carbon sequestration for changes in price of timber (P^T), price of carbon sequestration (P^{CO2}) and conversion factor ($conv$) in SEK/m^3/ha

Variables/ Values	Economic value Base scenario	Contribution of a one unit increment in temperature	length vegetation period
$P^T = 300$			
Timber:	769.35	769.35	769.35
Carbon Sequestration:	141.55	258.01	157.76
Total:	910.90	1027.36	927.12

$P^{CO2} = 300$			
Timber:	923.22	923.22	923.22
Carbon Sequestration:	262.13	477.80	292.15
Total:	1185.35	1401.02	1215.38
Conv=0.485			
Timber:	923.22	923.22	923.22
Carbon Sequestration:	70.77	129.01	78.88
Total:	993.99	1052.23	1002.10

Table A2: The total economic benefit of timber production due to an average contribution of a one-unit increase of temperature and the length of the vegetation period in SEK.

P^T= 360

Timber: 3.00 10^9* 360= 108.00 10^{10} SEK

P^T=300

Timber: 3.00 10^6 *300= 90.00 10^{10} SEK

Table A3: The comparison of the total economic value of the timber production and the gross domestic product (GDP) in 2018.

P^T= 360

Timber: 3.00 10^9* 360= 108.00 10^{10} SEK

GDP (2018): 551.032 10^9*8.5315= 470.1129508 10^{10} SEK

(TOTAL TIMBER VALUE /GDP (2018))*100= 22.97% of the GDP (2018).

P^T= 300

Timber: 3.00 10^9* 300= 90.00 10^{10} SEK

GDP (2018): 551.032 10^9*8.5315= 470.1129508 10^{10} SEK

(TOTAL TIMBER VALUE /GDP (2018))*100= 19% of the GDP (2018).