Investigating the Prerequisites of a Service Guarantee for Soil Damages

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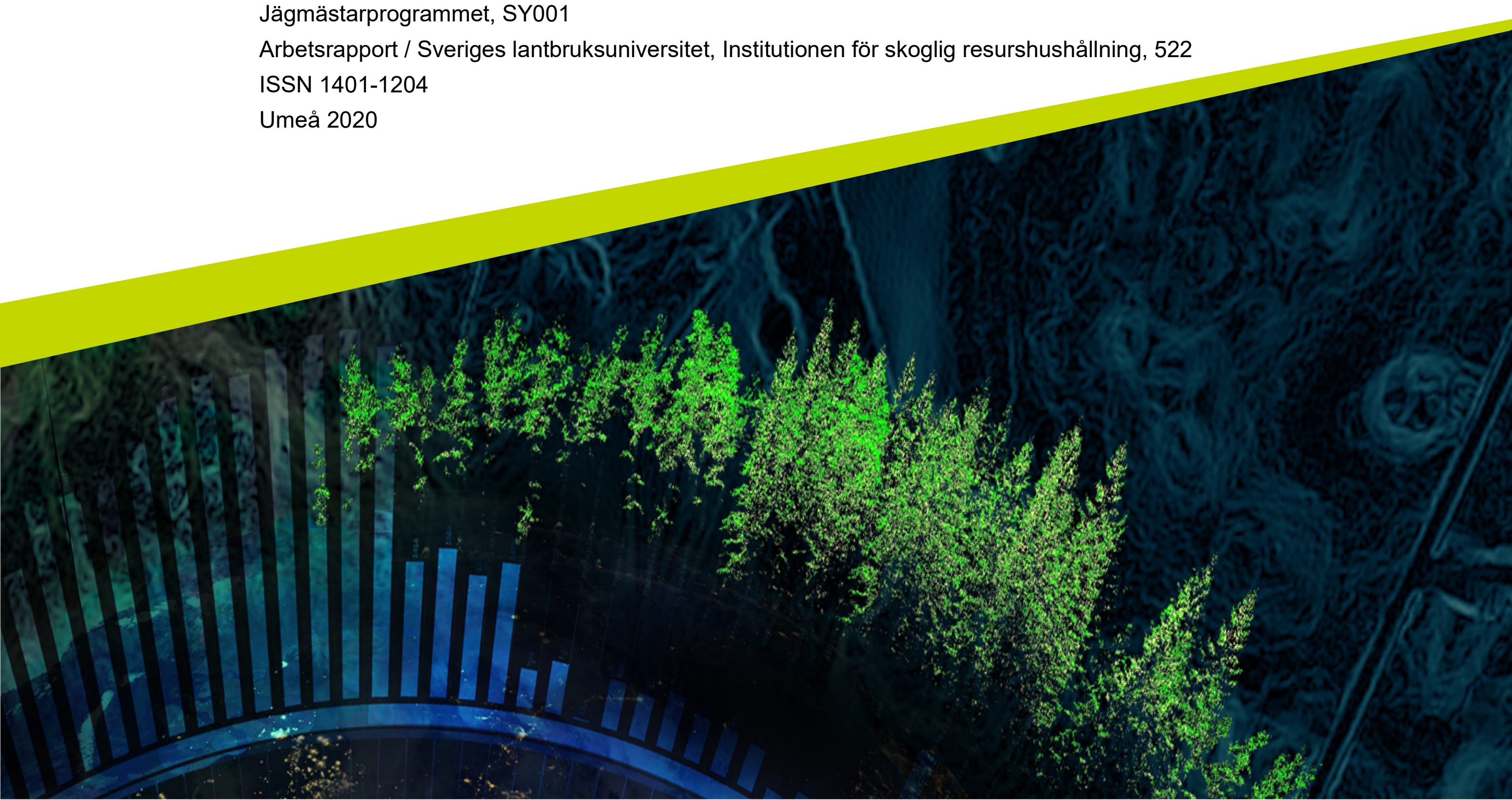

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Abstract

Timber harvesting is a disturbance which can alter the natural order of the ecosystem, causing potentially harmful consequences, especially on water quality. These damages are commonly present where forestry machines have ruptured or compacted the organic layer of the forest floor. Therefore, protection of forest soil during forestry operations has become an increasing concern, and many forestry companies are actively working towards implementing soil protection strategies. SCA Skog AB proposed the possibility of implementing a service guarantee as a strategy to meet this goal.

Therefore, this project was undertaken to investigate the prerequisites of creating a service guarantee for soil damages. In this study, the aim was to assess the possibilities to create a predictive model and to use the model result as an input to calculate the cost of implementing the service guarantee. A binomial logistic regression analysis method was used, and purposeful selection was chosen as the method of selecting variables for the predictive model. Data were provided by SCA Skog AB.

The result of this investigation shows that the current dataset is not suitable for creating predictive models. Although it was possible to detect correlation between the independent variables, and rutting and severe rutting, it was not strong enough to be used in a prediction model. As it was not possible to predict the risk of rutting and revere Rutting, an average was calculated to provide the expected number of soil damages detected each year. Thus, the second aim, to calculate cost estimate intervals for a guarantee was possible to fulfill. Depending on the chosen Soil Damage Recovery Scenario, Assessment Sample Size, Employee option and Forest Owner Compensation, it was concluded that the implementation cost of the service guarantee should range between 347 028 and 2 012 254 SEK/year in total costs for the studied area, which would be equivalent to 0.41 - 2.25 SEK/m^{3}sub (cubic meters, solid volume under bark).

Keywords: Service Guarantee, Soil Damages, Forestry, Soil Conservation, Predictive modelling.

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1. Introduction

Utilization of the forest as a natural resource has been a part of the Swedish history for many centuries and has shaped the forest landscape to a large extent. In the pre-industrial era, timber harvesting for domestic use, collection of wood fuel and creation of charcoal and potash were important uses of the forest. Large scale extraction of forest products started in the 13th century when the mining industry expanded, and accelerated further with the industrialization in the mid-1800s (Royal Swedish Academy of Agriculture and Forestry, 2015). The forest resource has been stated to be the backbone of Swedish socio-economic development (Oosthoek and Hölzl, 2018).

Large-scale exploitation in the mid-1800s led to extensive depletion of the Swedish forests which called for action. The first step was the declaration of the Swedish national forest policy and Forestry act in 1903 (The Royal Swedish Academy of Agriculture and Forestry, 2015). The 20th century is characterized by realization that the forest is a limited resource if not managed right. Hence, the concept of sustainability made its way into Swedish forestry. In the early 20th century this concept became a state enforced law and policy which focused mainly on regeneration, economic revenue and public use. This was a reaction towards increasing demand caused by industrialization, the great depression and the second world war (Oosthoek and Hölzl, 2018). However, the late 20th century and early 21st century was instead characterized by a rising awareness of the ecological importance of the forest ecosystem. Protection measures such as the Hormoslyr Banning in 1977 and declaration of the current Forestry law in 1993 (which equalized the ecological and production values), are just a few examples (Royal Swedish Academy of Agriculture and Forestry, 2015).

The forest's role as the most ecologically important terrestrial ecosystem has been brought to attention over the last decades. It is estimated that 75 % of the world's accessible freshwater for agricultural, domestic, industrial and environmental uses comes from forests (FAO 2020). In Sweden, forests cover about 69 % percent of the land area (Statistiska Centralbyrån, 2014) and holds 100 000 km of watercourses (Lindegren, 2006). The forest ecosystem is crucial in providing essential ecosystem services and is sensitive to disturbances (Pettersson, 2017).

Timber harvesting is a disturbance which can alter the natural order of the ecosystem, causing potentially harmful consequences, especially on water quality. These damages are usually found where forestry machines have ruptured or compacted the organic layer of the forest floor, in skid trails and logging roads (Lee, 1980; Cambi *et al.*, 2015). More specifically, ground-based harvesting can cause increased sedimentation and erosion, changes in water temperature, chemistry and disruption of the normal nutrient cycle. Therefore, protection of forest soil during forestry operations has become an increasing concern, and thus many forestry companies are working actively towards implementing soil protection strategies.

To meet the rising environmental awareness in the forestry industry today it is important for forestry companies to be perceived as sustainable and trustworthy; therefore, forestry companies put much effort into showing they take environmental values into consideration when planning and executing forestry operations. One strategy to achieve this goal is through the implementation of a service guarantee. While the service guarantee is extensively established in many business areas, it has not yet become adopted into the forestry sector. In a service guarantee regarding soil damage prevention, the forestry company obligates itself to make sure that limited damage is done to the soil during harvesting and forwarding. A service guarantee can be a powerful tool, not only to gain market recognition and attract new customers, but also to develop and improve performance standards (Hart, 1998; Wirtz, 1998; Wirtz and Mattila, 2001; Fabien, 2005).

2. Objective and Study Questions

The overarching objective of the study was to evaluate the possibilities for implementing a service guarantee for soil damages in a large Swedish forest company. The aim of the study was to create a framework and an information basis for the decision-making process for future development and implementation.

The study aimed to answer the following questions;

- Is it possible to predict soil damages using data which are readily available through the forest company's regular information systems?
- What is the probability of severe soil damages after ground-based harvesting operations?
- Which factors have the highest contributing impact for severe soil damages?
- Which factors need to be taken into consideration when creating a guarantee cost estimate?

By meeting these objectives, this study provides an important empirically based input to understand and possibly mitigate soil damages after mechanized harvesting. Most importantly, by meeting these objectives the study provides insight to the possibilities of predicting soil damages using extensive datasets which are collected over long time-periods and are readily available to most forest companies.

3. Background

3.1. Soil Damages in Forestry

Forestry machinery is necessary for efficient wood extraction which is needed to provide the wood-processing industries with sufficient raw material. However, mechanized harvesting also requires heavy machinery. In Sweden the typical weight of a harvester ranges between 11 and 20 Mg. The total mass (curb weight plus maximum load) of an average forwarder used in Swedish forestry is approximately 20 – 40 Mg (Nordfjell *et al.*, 2019). Naturally, the heavy machinery has an impact on the forest soil. An impact which has potentially harmful effects on soil structure, biota and stand environment.

This section covers the two main categories of soil damages - compaction and rutting - their potential environmental impact, and the factors which has the most significant role that are preventing or conducive to soil damages.

3.1.1. Soil Compaction

Soil compaction is considered the most common type of damage related to mechanized, ground-based harvesting. Compaction occurs when the soil is exposed to forces which exceeds its natural internal mechanical strength or resistance (Cambi *et al.*, 2015; Magnusson, 2015). In addition, there are many natural processes which can also cause compaction i.e. fluctuations in temperature and hydrology, animal trampling or earth movements (Hillel, 1998). However, human induced forces caused by forestry operation activities causes an unnatural vertical force which comes with a set of potentially detrimental consequences (Magnusson, 2015). Existing research establishes that soil compaction is generally viewed as a negative consequence of forestry operations. This study focuses exclusively on these hazardous effects of soil compaction, even though there are instances where soil compaction has a positive effect on plant growth.

Ampoorter et al. (2007) found that compaction caused a decrease in soil porosity, more specifically macroporosity, which chiefly affected the soil drainage and increased surface runoff. This structural change in the soil horizon affects water infiltration and permeability, as well as air permeability and oxygen supply (aeration). While a higher ratio of macropores usually leads to a higher water retention (Currie, 1984) it might not lead to higher plant-available water content. Furthermore, Wästerlund (1985) discovered that compaction of soil structure increased the penetration resistance, which in turn inhibited the root growth. This result agrees with the findings of a more recent study carried out by Taylor and Brar in 1991.

Moreover, changes in soil porosity have a substantial impact on soil biota. While the severity of compaction largely varies with the soil properties, it typically has a negative outcome for soil organism communities. Negative changes in porosity, pore size distribution, connectivity and the air/water ratio normally results in a reduction in soil fauna as well as in microbial biomass and activity (Frey *et al.*, 2009). Especially trails and log landings have proven to hold the least favorable soil conditions. Lower porosity in addition to increased bulk density, mechanical resistance and altered water, oxygen, carbon and nitrogen concentrations makes the trails and log landings inhospitable to natural regeneration (Pinard, Barker and Tay, 2000; Blouin *et al.*, 2005).

Determining exactly which factors that affect the probability of compaction is difficult. The challenge lies in isolating the affecting factors, since it is more likely a joint impact of several factors which causes the risk of compaction. In an effort to summarize the existing body of literature, Cambi et al. (2015) compared and compiled the results of several studies to examine which factors that had most impact on soil damages related to mechanized harvesting. They found that some of the most significant factors were related to the works characteristics. Logically, the number of trips and the weight of the vehicle had a significant role in relation to occurrence of compaction after harvesting operations. These results corroborates with Williamson and Nielsen (2000) who showed that 62 % of the bulk density compaction occurred in the top 10 cm of the soil after only one pass of the harvester. However, the reduction of flow channels due to compaction continued up to the sixteenth pass of the forestry machine (Cambi *et al.*, 2015). Cambi et al. (2015) also found that the harvesting system did not have any substantial contributing impact to compaction, the “cut-to-length”-system (CTL) (which is commonly used in Sweden) showed no significant difference when compared to the “whole-tree”-system (WTS). Forwarders in Sweden are usually wheeled or semi-tracked. Tire and track gave the same results in the studies conducted by Jansson and Johansson (1998). Wheel inflation pressure proved to have small a role in causing compaction, although not substantial.

In addition to the mechanical characteristics, there remains several aspects of the stand and soil characteristics to explain the risk of compaction damages. Such an aspect is slope gradient, which has a moderate contributing impact to compaction. However, it is noteworthy that harvesting direction combined with slope gradient had a significant correlation to compaction damage. Jourgholami et al. (2014) investigated this correlation and found that forwarding logs uphill in 0-10% slope had great impact on bulk density, penetration resistance and total porosity. In contrast, forwarding in a downhill direction only had a minor impact.

Several studies which were reviewed by Cambi et al. (2015) collectively concluded that lower soil bulk density typically increases the risk of soil compaction. This phenomenon also applies to higher particle size distribution and organic matter content. Hillel (1998) found that high soil water content increased the risk of compaction (due to decreased frictional forces and particle-to-particle bonding) until a critical moisture content, at which the susceptibility decreases. Hillel (1998) also presented that water levels above the critical moisture content eventually increases the risk of topsoil churning and puddling. This result is supported by Williamson and Nielsen who conducted a similar study in 2000. Some preventing factors were identified in the literature review by Cambi et al (2015) as well, such as frozen soil water and high aggregate stability.

3.1.2. Soil Rutting

Rutting has been defined broadly as the most evident outcome of soil compaction. Horn et al. (2007) defines rutting as "the result of vertical and horizontal soil displacement to either the middle or the sides of the skid trail associated with the shearing stresses and soil compression in moist or wet soils". There has been many attempts to defining ruts, however the most apparent definition might be to simply state that ruts are formed when the soil bearing capacity cannot cope with the weight of the forestry machine. Unlike compaction rut formation occurs when a visually detectable cavity in the soil is created due to soil displacement from track/tire forces (Horn, Vossbrink and Becker, 2004; Horn *et al.*, 2007).

The consequences of compaction is to a large extent also associated with rutting. Generally, except for a few wet and saturated soils, rutting also comes with compaction damages. These damages are mainly located along the sides and the bottom of the rut (Arnup, 1998). The displacement of the topsoil and compaction related to the rutting is associated with a number of ecologically harmful impacts. While the consequences of compaction is applicable to rutting, there are some damages exclusive to rutting.

A serious problem caused by deep rutting is erosion and nutrient leakage to watercourses. Magnusson (2015), explained that the main causes of erosion in ruts are due to increased exposition of mineral soil to rain and surface runoff. Rutting inhibits the water infiltration and often causes puddling which in turn causes waterlogging and surface runoff. Deep ruts becomes preferential routes of water movement, with detrimental erosion as effect, especially in steep terrain (Bagheri, Naghdi and Moradmand Jalali, 2013). The accumulation of water in saturated soils can cause landslides or mudflows (Cambi *et al.*, 2015). Suspended organic and inorganic particles can cause soil sedimentation of waterways and eutrophication of water bodies (Blanco-Canqui and Lal, 2008; Magnusson, 2015).

On flat terrain, deep rutting causes rainwater to accumulate which can lead to formation of methylmercury; especially during wet conditions. Methylmercury is transported with runoff along with organic matter and over time, the accumulation of methylmercury in organisms living in aquatic ecosystems can reach hazardous levels. There are several studies pointing towards increased levels of mercury and methylmercury in water courses and ditches due to adjacent harvesting (combined with site preparation), and severe soil damages (Magnusson, 2015).

In their extensive literature review, Cambi et al. (2015) summarized the factors that had most impact on rutting related to mechanized harvesting. Similarly, to compaction damages, many of the work characteristics had a substantial conducive role in causing rutting damages as well. Several articles in the review agreed that the ground contact device positively influenced the existence of rutting, where wheels seemed to be related to the highest risk of rutting, while bogie track and track had respectively moderate and low influence. Lowering ground pressure (and risk of rutting) was possible by increasing tire width and decreasing inflation pressure (Cambi *et al.*, 2015). The forwarder is usually a bigger cause of rutting than the harvester. The impact highly depends on the weight of the vehicle. Because the forwarder is heavier than the harvester and usually makes a greater number of back-and-forth trips, it is more often the cause of rutting. Generally, the number of trips that occur over the forest ground are considered to be an important factor (Jansson and Johansson, 1998; Jansson and Wästerlund, 1999; Bygdén, Eliasson and Wästerlund, 2003).

Stand and soil characteristics are important aspects of rutting as well as compaction. Cambi et al. (2015) found consensus in the statement that high moisture content increase the risk of rutting. Additionally, several studies of the review (Cambi *et al.*, 2015) clearly indicated that slope gradient had a clear correlation with existence and severity of ruts. Bagheri et al. (2013) stated that a slope gradient greater than 25% significantly increased risk of erosion.

3.1.3. Rutting as a Criterion for Soil Damage

Wronski et al. (1990) explained that rut depth and extent are often the only easily available criteria when assessing soil damages caused by harvesting. While compaction is possible to measure, it is not practical to implement during a standard post-harvesting assessment. Standard permitted rut depth, before harvesting operations are halted, is usually around 15-30 cm. Unfortunately, this type of visual assessment does not capture the entire range of soil damages caused by ground-based operations. Lacey and Ryan (2000) found that in the total harvested area, only 25 % of the soil damages were visually detectable, although 80 % of the study area had been subject to light and moderate compaction. These findings are supported by Aust et al. (1998) who found that visual disturbances are not representative of the entire site damage. Therefore, using visual assessment as the only criterion for soil damage severity might seem arbitrary. However, there are several reasons to why physical and chemical data sampling is not adopted. Schoenholtz et al. (2000) explains the challenges in establishing a soil health criterion biased on chemical and physical properties. They state that it is especially challenging "…because functions and subsequent values provided by forest ecosystems are variable and rely on the interplay of soil physical, chemical, and biological properties and processes which often differ significantly across spatial and temporal scales." Using these types of criteria would include choosing a standard set of soil properties as indicators, which would not be representative or generally applicable since the importance and influence of soil properties varies among forest ecosystems. Schoenholtz et al. (2000) further argues that a criterion which incorporates chemical and physical soil properties can only be adopted if they are; "sensitive to management- induced changes; easily measured; relevant across sites or over time; inexpensive; closely linked to measurement of desired values such as productivity or biodiversity; and adaptable for specific ecosystems". Based on these statements, the forest industry does not yet have the ability to incorporate such a criterion in their soil assessment.

3.2. Soil Damage Recovery

To date, there are few studies which focus on the recovery rate of soil compaction and rutting, and those that exist are almost exclusively short-term investigations. This indicates a knowledge-gap which will take a long time to fill. Hence, much uncertainty still exists about the relationship between soil damages and recovery rate, although it is possible to deduct some patterns from previous short-term research.

Recovery time, just like the risk of damage occurrence, is highly dependent on the soil properties. Physical properties such as slope, soil texture and chemical compounds have an important role in determining recovery time of compacted soils (Zenner *et al.*, 2007). Greacen and Sands (1980) discovered that soils that naturally are subjects to swell and shrink cycles (e.g. certain clay soils) recover faster than more coarse textured soils. Terrain slope along with intricate soil properties also affect erosion severity, which affect the recovery and severity of rutting damages. Furthermore, the recovery time varies in the different soil layers. The top 10 cm had recovered almost to its original state 5 years after harvest, while in 10-30 cm depth there were no such evidence (Page-Dumroese *et al.*, 2006). In their extensive literature review, Cambi et al. (2015) argue that since the depth and severity of the rut will determine time needed for recovery, more research in a variety of severity classes is needed in order to deduct a well-supported conclusion.

Biological soil and site properties also affect the recovery rate. The factors are numerous, and a few important examples are: organic matter content, biomass, soil biota and site specific vegetation. It is commonly believed that higher biological activity and recovery rate have a positive correlation (Cambi *et al.*, 2015).

3.2.1. Soil Damage Recovery Management

When soil damage has occurred, there is little which can be done to repair the damage. While the damage might be esthetically distasteful and inhibit accessibility, it is generally advised not to repair the damage at all, if possible. A common way of dealing with severe rutting is to use an excavator to even out the terrain and fill the cavities. However, while this solves the problem of esthetics and accessibility, it also increases the risk of erosion and leakages of nutrients and organic matter (Skogsstyrelsen, 2019).

The Swedish Forest Agency (Skogsstyrelsen, 2019) informs that action should be taken only in specific situations, such as;

- *When the damages cause leakage of loose matter to nearby lakes and watercourses*. In such a case, focus should be on redirecting water from the ruts and/or attempt to seal the ruts adjacent to the watercourse/lake.
- *When the damages cause erosion and landslide in steep slopes.* The course of action is similar to the one described above. Additionally, the ruts can be filled with forestry debris in order to slow the water flow.

One study conducted by Meyer et al. (2014) suggested that planting trees can improve soil structure recovery significantly. They studied recovery of forest soil from compaction in skid trails after planting black alder (*Alnus glutinosa* (L.)

Gaertn.). Remarkably, alder was capable of growing in harvesting trails with severely compacted soil, and that the regeneration of soil structure was significantly accelerated seven years after plantation. While the method is rather cheap and easy to implement, there are also limitations in specific species demands regarding site characteristics (e.g., climate, soil, water and light). Although the ruts themselves might not offer great conditions for tree growth, reestablishing vegetation cover in surrounding areas might reduce pressure on ruts, where the erosion risk is at highest (Alt, Jenkins and Lines-kelly, 2009). Increasing vegetation cover is a long term solution. However, Alt, Jenkins and Lines-Kelly (2009) present a number of suggestions for short-term solutions to avoid some of the sediment and organic matter transport during erosion. A selection of suggested tools used to reduce and redirect water flows are: different trail drainage designs, culverts, cross banks, recessed pipes, mitre drains and sedimentation dams.

Even though there are some guidelines aimed towards minimizing some of the harm caused by rutting, they are often impractical, inaccessible and costly. In conclusion, it is much easier to prevent forest soil damages than to repair them.

3.3. Soil Damage Prevention

3.3.1. Reasons for Soil Damages

The forest industry faces many challenges, and forest management no longer solely includes simple tree extraction. The situation is complex and requires thorough planning with consideration towards several factors. The industries need a steady flow of raw material throughout the year, and the requirements for different species and assortments varies (Skogskunskap, 2020). The forest companies have to provide the industries with the right resources and at the same time take into consideration the estrangements of the seasons and site specific requirements. Wet sites need to be harvested when the ground water is frozen or during the dry season. Unfortunately, the industrial need does not always match the natural preconditions. Additionally, extraction of biomass for bioenergy is increasing (Skogskunskap, 2020), which decreases available harvest residues for topsoil reinforcement. This complex situation often causes a pressure to harvest areas which are not optimal for the season and might lead to decisions that cause soil damages.

Moreover, there is always a certain level of uncertainty in the planning and operational process. Commonly, it is the forest manager who decides whether or not the site is suitable for harvesting. Current decision-making is commonly based on a couple of factors, especially hydrological site characteristics and time of the year. However, Lacey and Ryan (2000) studied the effects of clear-felling in a fertile *Pinus radiata* forest. The study was carried out in study plots which had been deemed by forest managers to be resistant to soil damages. The result still showed that 80 % of the study area had been subject to light-moderate compaction. 54 % of the study area was classified to have litter displaced and/or minor soil displacement, while 25 % showed cases of rutting (0.1-0.2 m). These results suggest that there are a few knowledge-gaps in the pre-harvesting process.

3.3.2. Soil Damage Prevention Strategies

Given the difficulties in repairing soil damages, the forest management directives are focused on methods to prevent soil damages. Prevention strategies can be implemented throughout the entire chain of events.

Planning

Perhaps the most important preventative tool is thorough planning based on detailed information about the forest (Skogskunskap, 2020). With good knowledge of the site damage resilience, it is possible to make well-supported precautionary decisions. Today, there are good decision-making tools such as hydrological maps and programs to calculate the optimal routes for harvester and forwarder. These tools can be a helpful supplement when planning the harvest unit. It is recommended that the majority of the planning process is conducted in field, preferably during the snow-free season when the features are easy to identify (Skogsstyrelsen, 2019; Skogskunskap, 2020). Usage of post analyses gives an opportunity to analyze the process and make improvements accordingly (Cambi *et al.*, 2015).

Using woody residues in forwarder trails

One of the most common recommendations to avoid soil damages is to leave woody residues in the harvesting and forwarder trails. This measure reduces the contact pressure between the machine and the soil, serving as topsoil reinforcement (Eliasson and Wästerlund, 2007). It is recommended to use at least 15-20 kg per square meter on highly susceptible soils. Moreover, it is important to keep in mind that the protective ability of the slash mat decreases with each machine pass (Labelle and Jaeger, 2012).

Time of harvest

Waiting for the right season is crucial in order to spare soil which is highly susceptible to compaction and rutting. Choosing to harvest during dry soil conditions or when the soil water is frozen will make load bearing capacity of the soil higher (Magnusson, 2015).

Machinery

Other recommendations to consider are using the most suitable ground contact device. Usually track or bogie track is most gentle. When using a wheeled machine it is important to adapt tire pressure and width (Cambi *et al.*, 2015).

Consideration towards hydrology

Extra consideration should always be taken in areas with high moisture content and in proximity to watercourses and lakes. Much damage can be avoided by reinforcing the trails, building bridges over watercourses and creating corduroy bridges in areas with low bearing capacity (Skogsstyrelsen, 2019).

Research aiming to develop and improve soil damage prevention strategies is steadily increasing and there are many suggestions. Horn, Vossbrink and Becker (2004) stated that avoiding compaction during ground-based harvesting using the technique available today is not possible. They also stated that the forest soils are not likely to recover and that this will alter future stand establishment, growth and resilience. They further conclude, supported by the findings in their studies that the only sustainable solution would be the usage of permanent harvesting trails. A permanent trail would limit the compaction damages to a specific area and spare the rest. These trails would have to be maintained in technically usable shape to be able to support long-term usage.

Another popular research area is the improvement of decision-making support. Disturbance prediction models and computer simulation models will likely be a more extensive tool in future planning. Such models would offer detailed information on site-specific requirements, enabling more well-supported decisions. Although, these models also need detailed input data and local calibration to operate at an desirable level (Reeves *et al.*, 2012; Hosseini, Lindroos and Wadbro, 2019). Unfortunately, detailed information and extensive precautions come with high costs, especially from a production economic perspective (Thees and Olschewski, 2017).

3.3.3. Prevention Strategies at SCA Skog AB

SCA has implemented a number of preventative strategies for their operations. These strategies are present all the way throughout the process, from strategical planning, to operational planning, through the harvesting operations and finally during assessment where conservation practices are being evaluated.

The method is called SED (SCA, 2018) which is short for "*Skonsam effektiv drivning*" and can be translated to "gentle/careful and efficient logging". The methodology is applied in all types of harvesting sites, both on tenures and company owned sites.

The goals of the SED-methodology are (translated from Swedish to English by the author);

- Decrease number of soil damages caused by ground-based operations
- Increase the number forest tenures possible to harvest when there is no snow-cover.
- Improved work environment for machine operators.
- Increased productivity.
- Practical/functional environmental conservation
- Increase the possibilities for logging residue extraction.

While the SED-methodology comes with a rather extensive handbook (SCA, 2018), some of the implementation guidelines are summarized and presented below in order for the reader to gain a basic understanding of the concept. The importance of defining the areas of responsibility throughout the process is stressed. The methodology has four main focus areas: log landing, strip road, main extraction trail and problem solving.

Log landing: The total volume from harvesting is transported to this area and is temporarily stored before being hauled by trucks to the end-users. Thus, the frequent driving in the area causes high ground pressure; extra consideration is required. Reinforcement of the strip roads closest to the landing using logging residues (slash) is recommended.

Strip road (*basväg*): In Swedish, the term *basväg* is defined as the connection between the log landing and the harvesting area, and in this study the term strip road is used as an equivalent term. The strip road is naturally subjected to high contact pressure between machines and soil. The closest strip road with sufficient soil bearing capacity should always be the first choice. Old strip roads with soil damages should be avoided. If possible, a new strip road should be created, preferably where there is forest present, which creates possibilities to reinforce the strip road.

Main extraction trail (*Huvudbasstråk*): In Swedish, the term *huvudbasstråk* is defined as the trail located in the forest (within the harvesting unit boundaries), on which most of the extraction is done, and in this study the term main extraction trail is used as an equivalent term. The concentrated volume of traffic on this main trail is high, and therefore it should be located on the part of the harvesting site with the highest soil bearing capacity.

Problem solving: It is important that the problem-based thinking permeates the entire process. Although, the planning process is the foundation of harvesting operations, both machine operators and production managers must always be prepared to adapt to unforeseen events.

3.4. The Service Guarantee

Kashyap (2001) stated that there is no existing single definition of the term "service guarantee". Based on this statement Hogreve and Gremler (2009) sought out to study the existing literature in search for consensus in the main components of a service guarantee. They found that most sources viewed a service guarantee as a promise or a policy which holds the service provider accountable for potential failures. For example, this promise could entail ensuring the customer of a certain quality regarding outcome in: the service, the service delivery process, or specific marketing-mix-elements (e.g. the price). From these service outcomes, the first two suggestions were best suited to the outline of this study. To increase credibility of the promise, the service guarantee also contains "compensation" as a significant feature. Including such a penalty has proven to serve as a powerful tool to increase accountability of the service provider (Hogreve and Gremler, 2009).

Hogreve and Gremler (2009) also created their own definition of a Service guarantee, derived from the 109 literature sources included in their study "Twenty years of service guarantee research: A synthesis";

> "A service guarantee is an explicit promise made by the service provider to (a) deliver a certain level of service to satisfy the customer and (b) remunerate the customer if the service is not sufficiently delivered."

There are many types of service guarantees with different functions. Wirtz and Mattila (2001) summarized the most common types of guarantee concepts and explained the guarantee scope. To avoid confusion, their terms and definitions are used without alteration and presented in Table 1.

Table 1. Definitions of guarantee designs, redrawn from Wirtz and Mattila (2001).

Term	**Guarantee scope**
Single-attribute specific guarantee	One key attribute of the service is covered by the guarantee
Multi-attribute specific guarantee	A few important attributes of the service are covered by the guarantee
Full satisfaction guarantee	All aspects of the service are covered by the guarantee. There are no exceptions.
Combined guarantee	All aspects of the service are covered by the full satisfaction promise of the guarantee. Explicit minimum performance standards on important attributes are included in the guarantee to reduce uncertainty.

Wirtz and Mattila (2001) made some important acknowledgements regarding the implementation of different guarantee scopes. They found in their study that the Combined guarantee (CG) was ultimately superior to the other guarantee designs. They found support in other literature which stated that Full satisfaction guarantees (FSG) are better designs than Attribute-specific guarantees. However, both the FSG and the CG are dependent on the customer's perception of satisfaction. There is a factor of subjectivity in the assessment of whether or not the quality of the service is satisfactory (Wirtz, 1998). In a service guarantee regarding potential harvesting damages the outcome would be assessed according to a set of criteria. While there surely are many definitions of "severe soil damages" it cannot simply be defined by the perceived level of customer satisfaction. Even if the customer perceives the quality of the service unsatisfactory, the actual harvesting operation is inevitably irrevocable. A service guarantee for soil damages would be completely built around specific performance standards of single or multiple measurable attributes regarding the acceptable level of severity and extent of the soil damages. Based on these arguments, the author of the present study concludes that the "Single-attribute specific guarantee" or the "Multi-attribute specific guarantee" would be most suitable in this case study.

3.4.1. Implementation of a Service Guarantee

Implementing a service guarantee can have potential impact not only on customer relations and sales, but also on the company's operations and service quality. Wirtz (1998) created a model based on existing literature to examine the impacts, benefits and challenges of implementing a service guarantee. They tested their model in four different case studies to supplement the literature. The model framework and the most important finding were structured and visualized in a figure which is redrawn and presented in Figure 1 which offers a comprehensive overview of the results from the study. A brief synthesis of some of Wirtz's (1998) findings is presented below.

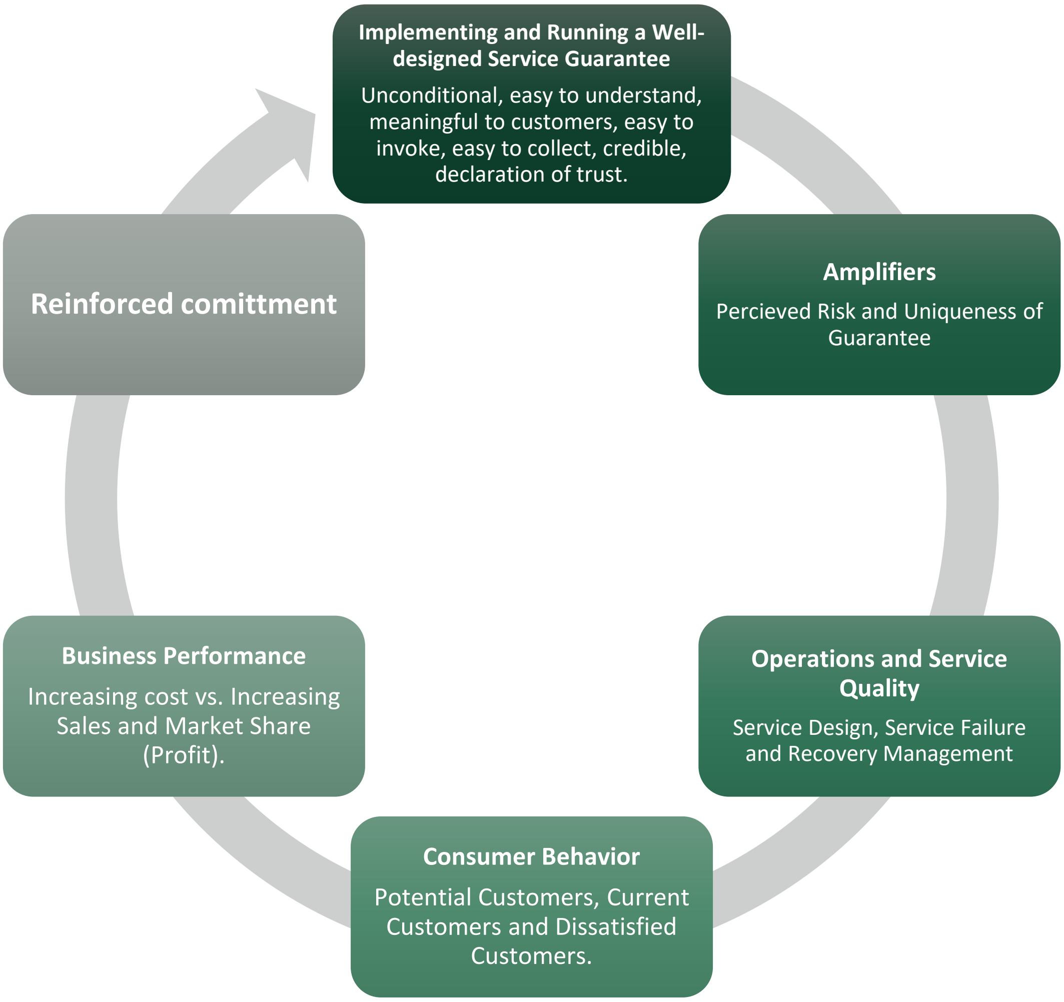

Figure 1. Impact and Development of a well-designed service guarantee model, Redrawn from J. Wirtz (1998)

Impacts on Operations and Service Quality

Service Design; In order to develop a successful service guarantee, the organization should also develop a well thought-through service guarantee design. It is generally believed that the creation of a service guarantee incentivizes the company to identify the performance expectations of its customers. "What is the customer's definition of good service?". Naturally the organization needs to improve the service delivery process and keep up with customer preferences in order to avoid increasing guarantee payouts.

Service failure and recovery management; Issuing a service guarantee leads to inevitable acknowledgement of some service failure. If the service failure is reoccurring it will result in an increasing number of payouts. While a large number of payouts will incur a certain cost, it will also turn up the pressure on recovery management. Wirtz (1998) states that "…every time a guarantee is invoked it provides an opportunity for the company to learn about potential fail points". This means that the company is pushed towards formalizing the service delivery process and ensures that the system is designed to meet the guarantee standards.

Personnel Management; Other than setting clear objectives for fine tuning of the service delivery process, the standard objectives for employees to adhere to is also clarified. It sheds light on what the company represents and defines each employee's role in achieving this ambition. Implementation of a guarantee can encourage to set internal standards throughout the operational process in a certain service quality, which can be used to train both new and existing staff.

Impacts on Business Performance

Previous studies which have explored consumer behavior implies that sales and market share could increase when implementing a service guarantee. While studies of actual income increment is limited, scholars suggest that "attraction of new customers, higher customer retention rates, increased brand loyalty and the ability to charge premium prices translate into higher sales" (Wirtz, 1998). Wirtz found all firms in the study reported that the guarantee had increased their sales and possibly also their market share.

Implementation of a service guarantee naturally comes with implementation costs. As mentioned earlier, the process cannot be and will not be completely failure-free, which incurs payout costs. The economics in the process of improving the operations in order to avoid payouts will have to be taken into consideration. Related costs depend on the original standards of the service. It is suggested that thorough research is needed in order to deduct the service elements most important to customers and which type of compensation/payout will be meaningful. In addition, legal considerations, guarantee design and marketing has to be well prepared. All of which incur costs. Wirtz (1998) discovered that all four firms in the study experienced short-term cost increases but that the benefits of the guarantee outweighed the costs in the long-term perspective.

Two amplifiers are suggested in the study; "Perceived risk" and "Uniqueness of the guarantee". The amplifiers are strictly related to impact on consumer behavior (not the operational process or internal structure), meaning that a higher perceived risk of the purchase will lead to a higher potential impact of the guarantee on consumer behavior. Additionally, Uniqueness of the guarantee also determine potential impact. Implementing a guarantee which resembles other guarantees in an already saturated market will lower the potential impact on consumer behavior. The higher the uniqueness, the higher the likeliness to attract new customers. However, even if the guarantee has little impact on consumer behavior there can still be significant impact in managerial aspects. Wirtz's model shows that a guarantee can be introduced for many different objectives, for example; gain market presence and quality reputation, turn potential customers into loyal customers, and increase operational and service quality.

The Dark side of Service Guarantees

While scholars suggest that the impact of implementing a service guarantee is mainly positive, there are also potential drawbacks;

- **Customer cheating;** most studies leave out the potential situation where the customer behaves opportunistically and misuses the guarantee in order to collect the compensation.
- **Raising doubts about the service quality;** implementation of a service guarantee can send the wrong signals. Rather than reassuring customers, the guarantee can serve as a signal that problems occur and increase the perceived risk.
- **Demotivating employees;** there is evidently limited research in the area. Some studies however imply that the negative customer feedback which comes with a guarantee can demotivate employees and lower the performance or feelings of well-being at work.

Moreover, there will always be some level of uncontrollable factors affecting service quality and customer satisfaction, which can pose future challenges.

3.4.2. A Good Service Guarantee

Hart (1998) suggests a couple of points to what a good service guarantee should include in order to successfully achieve service quality;

- A service guarantee should always be unconditional. Hart argues that real customer assurance means that the only important aspect is the customer satisfaction and no other conditions should be needed. It is not always possible to apply this to the entire service but will instead have to be applied to the elements which are possible to control. This is the case in an attribute-specific guarantee (Table 1).
- The premises of the guarantee should be easy to understand in order to create clear expectations, for both service providers and customers.
- The service guarantee needs to be meaningful. Hart argues that the service guarantee can be meaningful in two main aspects. The guarantee should put

emphasis on what is important to the customer, and it is crucial to have a clear understanding of what that would demand of the service. The guarantee also needs to be financially meaningful. Suggesting that the payout or consequence of service failure should match the severity of the seriousness of the failure.

- In order to avoid added dissatisfaction, the guarantee should be easy to invoke and easy to collect. Once a service failure has occurred it should fall upon the service provider to assist in the payout process.

3.5. SCA Skog AB – About the Company

SCA is the largest private forest owner in Europe. SCA owns and manages 2.6 million hectares of forest (of which approximately two million hectares are productive forest land) in northern Sweden and 30 000 hectares in the Baltics. The company also acquired an approximate volume of 430 000 cubic meters, solid wood volume including bark (m^3sob) from forest tenures during 2019. The company has been certified according to Forest Stewardship Council (FSC) since 1988 and according to the Program for the Endorsement of Forest Certification (PEFC) since 2011. SCA has its main office in Sundsvall but operates all over northern Sweden (Figure 2). SCA's three main production categories are timber, pulp and paper. Additionally, the company is currently the largest provider of bioenergy produced from forest material (SCA, 2019).

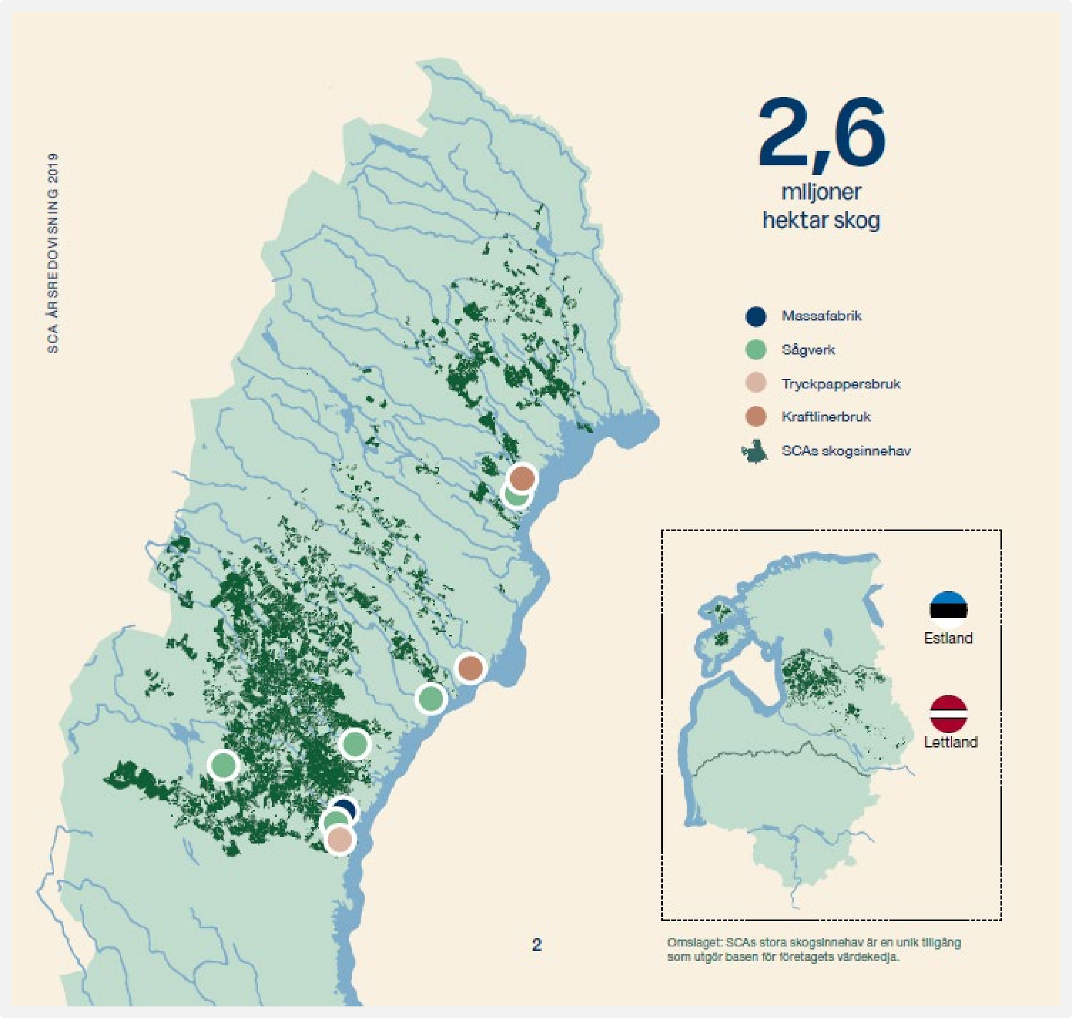

Figure 2. The Operative area of SCA Skog AB. Provided by SCA Skog AB (2020).

3.5.1. SCA's Motivation for the Service Guarantee

There are two main influential factors behind the initiative to create and implement a service guarantee to prevent soil damages;

One is as a reaction toward the occurring forest management situation. Hopefully, a service guarantee would acknowledge the importance of forest soil health and bring focus towards the need for best management practices. The forest industry must recognize the need for a sustainable utilization of the forest ecosystem. A guarantee would hold the company responsible towards a more thoughtful course of action.

Another purpose of a guarantee is to increase the company's reliability and accountability in the eyes of the private forest owners. A service guarantee could decrease some of the perceived risk and help SCA to establish increased market recognition as a sustainable forest company. The guarantee would ensure that SCA will take responsibility throughout the entire process, from preparatory planning, to harvesting operations and post-harvesting conservation measures. This would ensure that wood extraction is carried out in an efficient, responsible and gentle manner to minimize the amount of soil damages. If the management does not live up to the quality as promised an inquiry will be created and the forest owner will be compensated.

4. Method and Materials

4.1. Research Approach

A case study approach was chosen to allow deeper insight into the process of dealing with soil damages on a company level. The benefit of this approach is the opportunity to capture the complexities of the phenomenon in a project which is manageable within the given time limit. A quantitative research design with focus on data collection and statistical analysis was used. Additionally, a mixed research approach was implemented in the section regarding economic calculations because some of the input data were based on assumption i.e. estimates of costs such as salary, travel costs.

4.2. Study Area

The study area consisted of SCA's West Bothnia region, which is a geographical region defined by the company. SCA had, at the time of the study, defined the region as the same as the political boundaries of West Bothnia (*Västerbotten*) county, located in the north of Sweden (Figure 3). Included in the study were all areas harvested (final felling) by SCA during 2009-2019 in the West Bothnia region. Both company-owned forests and area-based tenures (a three-year contract between SCA and an individual private forest owner which grants SCA the right to harvest the forest within a certain harvesting unit or forest estate) were included.

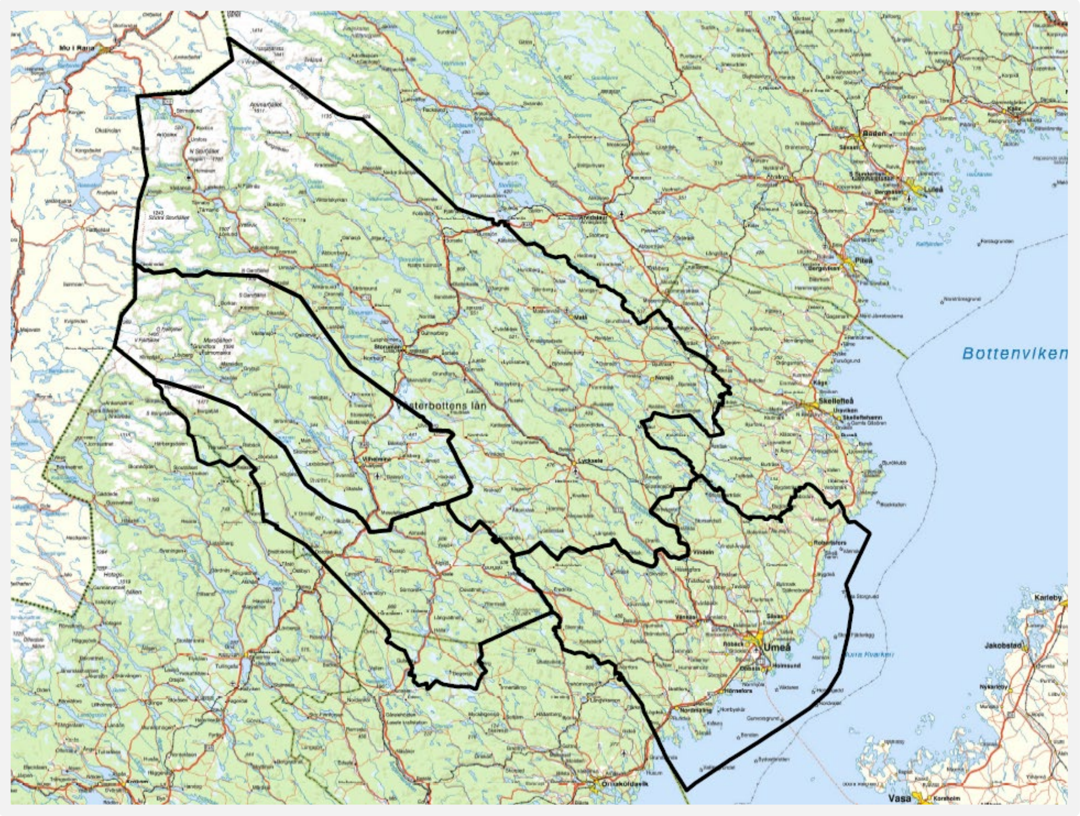

Figure 3. Boundaries of SCA's West Bothnia region, further divided into operational districts. Provided by SCA Skog AB.

4.3. Study Sample

The study sample data originated from SCA's Post-Harvest assessment for Environmental Conservation (SCA, 2018). The assessment follows a specific instruction where a set of variables are evaluated, which is carried out by field personnel and production managers after final felling. Post-harvest assessment is used to determine whether a harvesting operation has followed the forest management plan and SCA's prescribed practices. The assessment provides an important information basis for identifying areas in need of improvement.

Post-harvest assessment includes soil damage assessment. Soil damages are further divided into two categories: rutting, and severe rutting. In this study the dependent variables are the number of harvest units where rutting and severe rutting was present. Each harvesting unit is viewed as one sample plot because the assessment grading is based on the attributes of an entire harvesting unit.

Rutting and severe rutting are defined according to SCA's internal guidelines. Each soil damage category is assessed based on several assessment criteria to describe the damage.

Rutting is defined as a cavity caused by a forest machine which does not affect any watercourses, lakes or hydrological conservation areas, and fulfills one or more of following criteria:

- Deeper than 30 cm and covers more than (average) 20 m/hectare.
- Deeper than 30 cm and covers more than (average) 10-20 m/hectare AND the cavities/trails are obstructive and/or very visible.
- Deeper than 30 cm and covers (average) 10-20 m/ha AND affect frequently used recreational areas.

Severe rutting is defined as a cavity caused by a forest machine which affects nearby watercourses, lakes or hydrological conservation areas, and fulfills one or more of following criteria:

- Deeper than 30 cm and longer than 3 m AND within 10 m of a stream or other watercourse, lake, hydrological conservation area or mire.
- Deeper than 30 cm and longer than 3 m AND within the boundaries of a marked conservation area.
- Deeper than 30 cm and longer than 3 m AND in contact with a walking trail.
- Rutting in direct contact with a stream or other watercourse, stream slope and/or ditch which leads to a lake or larger watercourse.
- Rutting which might lead to sedimentation and/or transport of organic matter into a nearby waterbody.
- Has caused damming in proximity to a watercourse due to rutting or logging residues.

Each assessment criterion is given a grade from 0 to 5 which indicates the status of the assessed criteria, where; zero means that the criterion was not included in the study, 1-2 was failed and 3-5 passed. A more detailed description is provided in Table 2 and 3 (both Swedish and English translations included).

Table 2. Assessment Criteria Grading, in English.

Grade	Meaning	Pass or Fail
0	Missing	Excluded
1	Willful negligence. Not approved, unacceptable consideration to environment	Fail
2	Not approved, unacceptable consideration to environment	Fail
3	Acceptable consideration, but with deficiencies that requires restoration	Pass
4	Good, according to our instructions	Pass
5	Inefficient non cost-efficient consideration to environment	Pass

Table 3. Assessment Criteria Grading, in Swedish.

Betyg	Innebörd	Godkänd eller Icke Godkänd
0	Saknas	Exkluderad
1	Underkänd, mycket dålig hänsyn	Underkänd
2	Underkänd, bristande hänsyn	Underkänd
3	Godkänd men med vissa brister	Godkänd
4	Utmärkt	Godkänd
5	Övermål, ej kostnadseffektiv hänsyn	Godkänd

The nature of the assessment means that the only parameter recorded is the occurrence of rutting and severe rutting, not the extent or placement. Besides the distinction between rutting and severe rutting, the severity, number or extension of the ruts is not recorded in a way which is possible to analyze in this study. Since neither depth, length nor areal coverage of the soil damage is noted, the assessment simply states if there was soil damage present at the site or not. Hence, the dependent/outcome variable is binary.

The classification system also excludes soil compaction from the study. Rutting can result in compaction damages in proximity to the cavities. However, it is not measured in this current study.

The selection of harvesting units to be included in the post-harvest assessment is not consistent over the entire time period; therefore, the selection process cannot be viewed as random sampling because the subjects to be monitored have been chosen according to certain parameters. Sometimes the harvest unit is of particular interest, for example when certain circumstances cause higher risks of rutting or compaction. Other times the harvesting unit is simply included to fill the quota of number of field visits within a certain time period. Thus, a strict randomization process has not been implemented, which causes the experiment to resemble a nonprobability sample (or convenience sample), in which individual study plots are chosen based on their convenience and availability (Babbie, 1991). This poses a potential threat to the validity of the study and is important to keep in mind during data analysis. A convenience sample selection process can cause systematic patterns and differences in characteristics of the individual sample plots, which in turn can affect the result (Keppel, 1991). The statistical analysis requires a sample which is random and originates from objective sampling methods. However, there are many factors of subjectivity in the sampling method in this study and this needs to be taken into consideration. The data were treated as a completely random sample in order to be able to carry out the statistical analysis. Although, when dealing with the results it was crucial to treat the outcome with caution. The statistical approach was used to search for trends and patterns, the statistical significance (p-value) was of less importance.

4.4. Data Collection

All data used in the study were provided by SCA and extracted from their internal database. Data extraction and processing was carried out using Excel (Microsoft Office Professional Plus 2016) and the free software R (Version 3.6.3 (2020-02-29).

The sample plot data was retrieved from SCA's internal database for post-harvest assessment. The sample plot data from years 2009-2019 were exported into excel and filtered to only keep final felling, all other forms of harvest (e.g. thinning) were removed from the data. The original sample consisted of 1786 study plots collected from 2010 to 2019.

Forest and operations data were extracted from the internal database of SCA, to be used as complementary information of the sample plot data. Inclusion of all units harvested between June 2008 and February 2020 were carried out. The study only included years 2009-2019, although harvesting units from the last months of 2008 and the first months of 2020 were included to account for harvesting operations carried out at the end of the calendar years 2008 and 2020.

4.5. Data Processing and Statistical Analysis

4.5.1. Data Processing – Sample Plot Data

Data processing mainly consisted of removing duplicates from the sample plot data. Duplicates occurred when the same harvesting unit was assessed and registered by several different field personnel. However, to avoid over- or underestimating the number of soil damages in the data, duplicates were removed out of practical reasons. A few rules were established to determine which of the duplicates to keep. The duplicate was removed if;

- The sample plot assessment was less complete than the other(s), AND/OR
- The sample plot assessment had a better grade than the other(s), (the worst-case scenario was used in order to avoid underestimation of damages), AND/OR
- The sample plot assessment date was older than the other plot(s).

In total, 57 duplicates were found and removed manually. After processing, the dataset consisted of 1075 unique observations. Binary response variables "*Rutting*" and "*Severe Rutting*" were created and assigned to each harvesting unit. As described in section 4.3, the assessment for rutting and severe rutting is graded from 0-5. These grades were transformed into binary response variables, where grades 1-2 were classified as 1 (damage) and all other grades as 0 (no damage).

4.5.2. Data Processing – Forest and Operations Data

Duplicates appeared in several steps throughout the work process which required extensive troubleshooting. No duplicate entries of the same harvesting unit ID (unique identification number) was allowed in the dataset in order to build a representative predictive model. After removal of duplicates, the forest and operations dataset contained 8039 unique harvesting units.

The final set of independent variables and their respective unit is presented in Table 4. Several variables in Table 4 contain the same type of information. The reason behind this is that some of the original variables collected from the internal database had extreme outliers. New variables were calculated manually using existing data to find out if the outliers were a product of data export or internal database errors. Both variables were included in the prediction model building process, to investigate potential differences between the extracted and calculated variables.

Table 4. Variables included in statistical analysis and model building, and variable unit.

English Variable Name	Unit
Works Characteristics	
Harvesting Unit Identification Number (ID)	7 digits, unique number
Mean volume/ha reported by the forwarder	m^3sub/ha
Mean volume/ha reported by the harvester	m^3sub/ha
Total harvested volume	m^3sub
Harvested volume/ha	m^3sub/ha
Average forwarder load size	m^3sub/load
Mean stem volume	m^3sub/stem
Computed mean stem volume	m^3sub/stem
The total forwarding distance	m
Harvester trail length	m
About the Harvesting Unit	
Terrain inclination	1-5
Terrain Structure	1-5
Snow factor	%
Spruce proportion[1]	%,
Pine proportion[2]	%
Deciduous species proportion[3]	%
Obstructing undergrowth	Trees/ha
Obstructing trees proportion[4]	%
Harvest Unit area	ha
Other	
Month 1	Nominal
Month 2	Nominal
Year	Nominal
District	Nominal
Forest Origin	Nominal

[1] Proportion of harvested Spruce volume, out of total harvested volume (m^3sub).
[2] Proportion of harvested Pine volume, out of total harvested volume (m^3sub).
[3] Proportion of harvested Deciduous volume, out of total harvested volume (m^3sub).
[4] Proportion of obstructing trees, out of total number of harvested trees.

First date of forwarding operations indicates which date the actual forwarding began in the given unit and is derived from the first files of production reporting sent from the forwarder. The *First date of forwarding operations* was used to derive the variable “Month 1”. False reporting from the forwarder caused the same harvesting unit to have several first dates of forwarding operations which created duplicates in the data. These duplicates were removed systematically by excluding the oldest production files.

Last date of forwarding operations is the variable used to indicate the last date of the forwarding operations and is derived from the last files of production reporting sent from the forwarder. The *Last date of forwarding operations* was used to derive both the "Year" and "Month 2" assigned to each harvesting unit. False reporting from the forwarder also caused the same harvesting unit to have several last dates of forwarding operations which created duplicates in the data. These duplicates were removed systematically by excluding the most recent production files.

*"*District*"* represents the area controlled by one production manager, and is sometimes called the wood flow range. The same harvesting unit can be assigned to several districts which causes duplicates in the data, which were removed by random selection.

"Terrain Structure" describes the terrain's difficulty for forestry operations. It is a standardized term (Swed. *Ytstruktur*) commonly used in the forestry sector (Berg, 1992). Each Harvest Unit is given a "Terrain structure" grade, from 1-5, which states the difficulty for forestry work. The grade is based on the presence and quantity of forest terrain obstacles in various size-classes. The "Terrain structure" was statistically analyzed both as a factor and a continuous variable.

"Terrain inclination" (Swed. *Lutning)* is also graded from 1-5 and represents an average inclination of the entire harvest unit. A more detailed description of the inclination-grades is given by Berg (1992). The "Terrain inclination" was also statistically analyzed both as a factor and a continuous variable.

Outliers which were detected in the (forest and operations) dataset, were removed systematically by introducing maximum thresholds. All values exceeding that threshold were removed and replaced with a missing value ("NA" in R).

The variable *"*Mean Stem Volume*"* had 14 units with extreme values. The "Mean Stem Volume" ranged from 0 - 3 285 m^3sub (solid under bark) per tree, with a median of 0.187 m^3sub. All values above 4 m^3sub were removed.

"Forwarder load-size" also had extreme outliers. The range of the variable was 0 – 2 559 m^3sub, with a median of 15.85 m^3sub. Given the technical limitations a forwarder load-size of 25 m^3sub is considered extreme. Forwarder load-sizes larger than 30 m^3sub were removed, which applied to 84 units.

"The total forwarding distance" (TFD) is the combined distance travelled along the main forwarding road, both within the harvesting unit, and the distance between the log landing and the harvesting unit outlines. This is the road which carries the accumulated wood volume transported from the forest to the log landing, and is therefore subject to a higher risk of soil damages. The TFD is an estimated distance based on the GPS (Global Positioning Systems) tracking of the forwarder.

Two other variables which were included in the original dataset were “Total wood volume” and “Harvest unit area” (measured in hectares). Although, they were both used individually as input variables, they were also used to create a new variable; “Harvested volume per hectare”, used as a variable of comparing the mean harvested volume density between the harvesting units. With this variable it was possible to somewhat isolate and study the impact of standing wood density on soil damages. However, the calculation created some outliers which were removed from the dataset. The range of the variable was from 0.0 - 10 899.9 m^3sub/ha, while the median was 142.1 m^3sub/ha. This problem was believed to have multiple explanations. The first problem identified was that some harvesting units had an area of zero ha. In an initial stage of the data processing these were believed to be very small harvesting units (<0.5 ha) which simply have been converted to 0 ha when rounding to integers. A rule of turning all of these into units of 0.5 ha was applied in order to avoid “infinite” numbers in the calculations. Some units probably were much larger and had a high total volume, but for some reason were missing the unit size. Dividing these volumes by an area of 0.5 ha thus generated a very high volume per hectare. The limit was set to 3 000 m^3sub/ha and 18 harvesting units outside the limit were removed.

4.5.3. Training and Test Data

The sample plot dataset was merged with the forest and operations dataset using the harvesting unit ID as a link. The new dataset was divided into a training dataset and a test dataset. The training data is a sample of the data used to train the model, and a test dataset is a sample of data used to evaluate the model fit or forced adaptation of the model to the existing dataset (cross validation). The training-test split-ratio was based on the number of observed sample plots where damages (1’s) were present and was set to 7:3. The 0s and 1s were randomly selected and included in the training and test datasets. The training and test data were created the same way for both dependent variables, although using respective response variables to create the datasets.

4.5.4. Building the Predictive Model

Many models were developed in the training process. The Binomial Logistic Regression analysis method was chosen because the independent variables were of both categorical and quantitative nature, and the response variables were of binary nature. Binomial logistic regression also allows to test for the interdependence of the independent variables, which was preferable given the extensive number of variables included in the analysis. Significance levels were set at 0.05.

A multinomial logistic regression model was also an option for the prediction model. A multinomial logistic regression model would have been a possible option for the predictive model as well. However, because both rutting and severe rutting can exist in the same harvesting unit at the same time, a multinomial logistic regression model would have generated four possible outcomes; no damage, only rutting, only severe rutting or both rutting and severe rutting. Because the number of observed damages was already few, it was argued that it would not benefit the result to divide the dataset further.

The method of selecting variables and developing the model in this study is largely following the steps of "Purposeful selection" as described by Hosmer et al. (2013). Below, each step of the model building process applied to both the rutting and severe rutting prediction model, are described.

Step 1. A univariable analysis of the independent variables. The analysis was carried out using the following generalized linear model (in R, "glm()-function", combined with the "binomial" family) to obtain the estimated coefficient, the estimated standard error, Akaike information criterion (AIC) and the p-value.

In this first step of selecting variables, the p-value was of less importance. Using a traditional significance level (p-value <0.05) in an initial stage has been known to sometimes exclude important variables (Hosmer and Lemeshow, 2013). Instead, a higher significance level was accepted, and the AIC of each model was adopted as a mean of estimating the quality of each model. The AIC of each independent variable was compared to the reference AIC, which is the AIC from a model where the response variable is used as the only explanatory factor. All covariates with an AIC lower than this AIC were chosen as candidates for a first multivariable model.

Step 2. Identify independent variables with lower levels of statistical significance. In this step the traditional significance level (p-value <0.05) was used as a threshold. One covariate at the time was removed before proceeding to Step 3.

Step 3. For each covariate removed from the model, the AIC of the new model was compared to the AIC of the original model containing all the covariates included in Step 1. The process of deleting variables and validating in Steps 2 and 3, was repeated until all statistically unimportant variables were removed from the model, leaving only the important ones.

Step 4. All of the variables included in Step 1, which were excluded in Steps 2 and 3, were brought back into the model one at the time to check for significance. This is an approach to detect variables which are statistically insignificant by themselves but make an important contribution when combined with other covariates.

Step 5. The model was controlled for multicollinearity using the Variance inflation factor (VIF). 2.5 was the highest allowed VIF factor, as suggested by Paul Allison (2012).

Step 6. Assess the adequacy of the model and checking its fit in a process called cross-validation. This was done by applying the model built (trained) using the training data set, on the test dataset. Rutting or severe rutting was assumed to have occurred if the predicted risk was higher than 50%. The result was assessed by cross-validation between the training model prediction and the actual number of damages in the test dataset.

4.6. The Cost of Implementing a Service Guarantee

The total cost of implementing the service guarantee was estimated based on several factors (Figure 4): assessment sample size, soil damage assessment cost, soil damage recovery cost and forest owner compensation (payout). More detailed descriptions of each factor are provided in following sections.

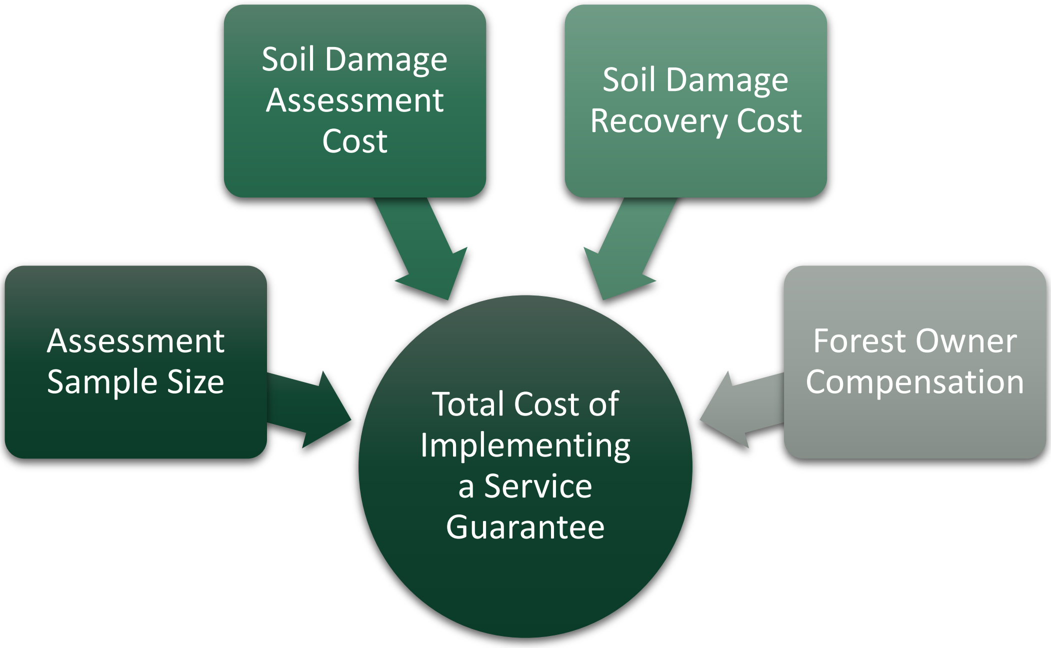

Figure 4. Visual representation of the factors contributing to the total cost of implementing a service guarantee.

4.6.1. Assessment Sample Size

Since none of the predictive models were able to predict the risk of rutting and severe rutting, a simple mean was calculated from the number of damages each year (2009-2019) and used in the cost calculation.

Six different *assessment sample sizes* were used in the study; 10 %, 20 %, 30 %, 40 %, 50 % and 100 %. Each sample size percentage equals how many harvest units were assessed out of the total number of harvested units each year. The number of damages detected was assumed to be proportional to the sample size. For example, if 10 % percent of the harvest units were sampled, 10% out of the total number of damages were expected to be detected. The mean area (hectare) harvested each year was calculated by dividing the total harvested area 2010-2019 by the number of years. A 10 % sample size was assumed to be equal to 10 % of the total harvested area each year.

4.6.2. Soil Damage Assessment Cost

The cost of soil damage assessment per year was calculated using data provided by SCA Skog AB in Umeå. The main factors which were assumed to affect the assessment labor cost (Table 5) were the following: number of working days, number of in-field days, number of administrative workdays, daily wage (SEK), average assessed area per day (ha), average distance driven per day (km) and transportation cost per day (SEK). Three possible employee options for assessment labor were identified: Full-time employee, Temporary employee and Contracted service. Each employee type was assumed to have different productivity, wage and days needed for administrative work. The days needed for administrative work was calculated as a set ratio, proportional to the number of days spent on field assessment.

Table 5. Total assessment labor cost (SEK) and additional information of each employee option. Provided by SCA Skog AB.

Factors	Full-time	Temporary	Contractors
In-field (days)	150	38	150
Administrative workdays (set ratio)	1,51	1,29	1,51
Total working days (= In-field days * set ratio)	**226**	**49**	**226**
Assessed area/day (ha)	25	20	25
Distance driven/day (km)	210	210	210
Daily wage (SEK)	3 509	2 457	2 800
Transportation cost/day (SEK)	734	734	844
Total labor cost/day (SEK)	**4 243**	**3 191**	**3 644**

The total soil damage assessment cost is presented as cost per year (SEK). The total cost varies with employee option and assessment sample size, as described further in Table 6-Table 8.

Table 6. Full-time employee. Assessment area, in-field days and total working days of each assessment sample size. "% full-time" represents the working days as a percentage of full-time employment total working days.

Sample Size	Assess. area (ha)	In-field days	Working days	% full-time	Total Cost
10 %	614	25	37	16	157 127
20 %	1 229	49	74	33	314 254
30 %	1 843	74	111	49	471 380
40 %	2 458	98	148	66	628 507
50 %	3 072	123	185	82	785 634
100 %	6 144	246	370	164	1 571 268

Table 7. Temporary employee. Assessment area, in-field days and total working days of each assessment sample size. "% full-time" represents the working days as a percentage of a Temporary employment total working days.

Sample Size	Assess. area (ha)	In-field days	Working days	% full-time	Total Cost
10 %	614	31	40	81	126 424
20 %	1 229	61	79	162	252 848
30 %	1 843	92	119	243	379 272
40 %	2 458	123	158	323	505 696
50 %	3 072	154	198	404	632 120
100 %	6 144	307	396	808	1 264 239

Table 8. Contractor. Assessment area, in-field days and total working days of each Assessment sample size. "% full-time" represents the working days as a percentage of full-time employment total working days.

Sample Size	Assess. area (ha)	In-field days	Working days	% full-time	Total Cost
10 %	614	25	37	16	134 936
20 %	1 229	49	74	33	269 872
30 %	1 843	74	111	49	404 808
40 %	2 458	98	148	66	539 744
50 %	3 072	123	185	82	674 680
100 %	6 144	246	370	164	1 349 360

4.6.3. Soil Damage Recovery Cost

The cost of soil damage recovery operations for one average harvest unit was calculated using data provided by forest management entrepreneurs contracted (at the time of the study) by SCA Skog AB in Umeå. Included in the cost of repairing rutting damages were following factors; labor cost (hourly rate), expenditure of time required for the repair work and expenses for relocating machinery. Three different *recovery management categories* were chosen in order to cover a range of possible damage-management strategies.

Category 1 – Severe rutting handled by an excavator
All soil damages which meets the criteria of severe rutting, must be handled by an excavator. In the case of rutting (which is not caused in proximity to or threatens to damage a hydrological consideration area) it is usually possible for the forest machine operator to repair the damage with the forestry machine already on site. However, when it comes to severe rutting damage repair measures a separate excavator needs to be brought on site. Costs of this process is presented in Table 9 and represent the average cost calculated from estimates by several entrepreneurs frequently hired by SCA at the time of the study.

Table 9. Category 1; the average cost of soil damage recovery operations per harvesting unit. Presented in Swedish Kronor (SEK).

Cost factors	***Cost (SEK)***	***Unit***
Machinery relocation	2 500	SEK
Hourly rate	713	SEK/Hour
Expenditure of time	4.25	Hours
Total labor cost	3 028	SEK
Total damage recovery cost	**5 528**	**SEK/Harvest Unit**

Category 2 – Rutting handled by a forwarder
In this category it was assumed that the rutting damages was detected and repaired by the machine operator on site, in which case no machinery relocation expenses would be added. Table 10 displays an average cost calculated from estimates by several entrepreneurs frequently hired by SCA.

Table 10. Category 2; the average cost of soil damage recovery operations per harvesting unit. Presented in Swedish Kronor (SEK).

Cost factors	***Cost (SEK)***	***Unit***
Machinery relocation	0	SEK
Hourly rate	844	SEK/Hour
Expenditure of time	1.75	Hours
Total labor cost	1 477	SEK
Total damage recovery cost	**1 477**	**SEK/Harvest Unit**

Category 3 - Rutting handled by an excavator
In this category it was assumed that the rutting damages were not detected by the machine operator on site, in which case an excavator would be brought on site to repair the damages. Table 11 displays an average cost calculated from estimates by several entrepreneurs frequently employed by SCA.

Table 11. Category 3; the average cost of soil damage recovery operations per harvesting unit. Presented in Swedish Kronor (SEK).

Cost factors	*Cost (SEK)*	*Unit*
Machinery relocation	2 500	SEK
Hourly rate	713	SEK/Hour
Expenditure of time	2.75	Hours
Total labor cost	1 959	SEK
Total damage recovery cost	**4 459**	**SEK/Harvest Unit**

4.6.4. Forest Owner Compensation

Because it is not always preferable to repair severe soil damages a payout option was created to compensate the forest owner when the damages were not repaired. This is the part of the guarantee which is issued to the forest owner when the company fails to deliver the promised service (the payout). The forest owner compensation only applies to harvesting operations carried out in forest tenures. In these harvesting units the severe rutting damages are not treated. Instead, half of the damage recovery cost is paid to the forest owner.

4.6.5. The Total Cost of Implementing the Service Guarantee

Because there is no general instruction to how soil damages should be repaired, three different *Soil damage recovery scenarios* were developed to provide a range of possible cost outcomes for the service guarantee. It is assumed that damage repair is applied in all units where severe rutting was present, in order to avoid underestimating severe rutting damage recovery costs. If the severe rutting damages are repaired, they were always assumed to be handled by an excavator. What actually changes in each scenario is the rutting damage recovery method. As requested by SCA, the damage recovery cost was calculated using harvesting units which are both company owned and tenures. The underlying motivation for this request was that soil damages should be treated equally regardless of forest origin. However, forest owner compensation only applies to forest tenures.

The three *Soil damage recovery scenarios* are listed below:

Scenario 1 – 100 % of rutting damages are handled by a forwarder

Scenario 2 – 50 % of rutting damages are handled by a forwarder

Scenario 3 – 100 % of rutting damages are handled by an excavator

In each of the *Soil damage recovery scenarios,* the *total cost of soil damage recovery management* was added to the *total soil damage assessment cost in* order to calculate the total cost of both assessment and damage recovery management. An additional option was added separately to each *Soil damage recovery scenario.* In this option, 50 % of the severe rutting damages detected in tenures are not treated. Instead, a payout is issued to compensate the forest owner.

It was assumed that the service guarantee implementation would create some additional administrative labor. Therefore, a 20% flat-rate administrative labor-cost is added to each scenario. The administrative labor-cost is assumed to be the same as the Full-time employee labor-cost.

Hence, the total cost of each soil damage recovery scenario is based upon following parameters;

1. Total cost of soil damage assessment
2. Total cost of soil damage recovery management
3. The total cost of forest owner compensation.
4. Total administrative labor cost.

The total cost was calculated per *year*, *Soil damage recovery scenario* and *assessment sample size* (which decides the number of detected damages and total area in need of assessment). The total cost was also presented as *Average cost per harvested* m^3*sub/year* as a reference to put in relation to other parts of the wood supply cost.

5. Results

5.1. The Predictive Model – Rutting

Step 1. The AIC-values from each univariate model is presented in Table 12. The AIC of the reference model was 297.02, which was set as a threshold for inclusion of independent variables before proceeding to *Step 2.*

Table 12. The AIC-values and Degrees of freedom from each univariate model. All variables below the reference threshold is denoted with bold

Independent Variables	**Df**	**AIC**
Reference	*1*	*297.02*
Obstructing trees proportion	2	**292.07**
District	21	311.70
Month 1	12	**272.90**
Spruce proportion	2	**291.79**
Obstructing undergrowth	2	**290.17**
Total harvested volume	2	**271.00**
Snow factor	2	**287.30**
Average forwarder load size	2	297.59
Deciduous species proportion	2	**287.42**
Terrain inclination (as factor)	32	334.13
Terrain inclination	2	**292.26**
Month 2	12	**268.41**
Mean stem volume	2	**290.74**
Harvest Unit area	2	**291.99**
Mean volume/ha reported by the harvester	2	**292.08**
Mean volume/ha reported by the forwarder	2	297.92
The total forwarding distance	2	298.21
Harvester trail length	2	**292.06**
Pine proportion	2	**290.98**
Computed mean stem volume	2	**291.14**
Forest Origin	2	**296.08**
Harvested volume/ha	2	**273.55**
Year	11	**285.80**
Terrain Structure (as factor)	32	317.46
Terrain Structure	2	**292.10**

Steps 2 and 3. The first model (Model A) was created from all independent variables with an AIC lower than the reference AIC. Note, that the variable “Year” was used only in Model A. It was later removed from the dataset because this was only meant to be used as a reference/explanatory variable. Several variables lost their statistical significance when this variable was removed (Model B). Binomial regression analysis showed that none of the independent variables in Model B were statistically significant. Table 13 and Table 14 display the differences in statistical significance between Model A and Model B. Variables “Year” and “Month 2” had very high VIF-values when both were included in the same model, regardless of which other covariates were included, which indicated that these should not be implemented at the same time. The variable “Month 2” always had a higher statistical significance than “Year” and was therefore the covariate to keep in proceeding model development.

Table 13. Model A containing all independent variables with an AIC lower than the reference AIC. Model AIC = 277.88

Independent Variable	**LR Chisq**	**Df**	**Pr(>Chisq)**
Obstructing trees proportion	0.70	1	0.40
Month 1	9.77	11	0.55
Spruce proportion	0.20	1	0.65
Obstructing undergrowth	2.37	1	0.12
Total harvested volume	0.59	1	0.44
Snow factor	0.38	1	0.54
Deciduous species proportion	0.41	1	0.52
Terrain inclination	2.34	1	0.13
Month 2	15.27	11	0.17
Harvest Unit area	0.08	1	0.78
Mean volume/ha reported by the harvester	0.01	1	0.92
Mean stem volume	6.38	1	**0.01**
Harvester trail length	0.08	1	0.78
Pine proportion	0.19	1	0.67
Computed mean stem volume	6.28	1	**0.01**
Forest Origin”	0.65	1	0.42
Harvested volume/ha	0.10	1	0.75
Year	25.42	10	**<0.001**
Terrain Structure	2.10	1	0.15

Table 14. Model B containing all variables from Model A except "Year". Model AIC = 283.30.

Independent Variable	LR Chisq	Df	Pr(>Chisq)
Obstructing trees proportion	0.49	1	0.48
Month 1	9.35	11	0.59
Spruce proportion	1.14	1	0.29
Obstructing undergrowth	2.06	1	0.15
Total harvested volume	0.03	1	0.86
Snow factor	0.33	1	0.57
Deciduous species proportion	2.51	1	0.11
Terrain inclination	1.25	1	0.26
Month 2	16.38	11	0.13
Harvest Unit area	0.001	1	0.97
Mean volume/ha reported by the harvester	0.92	1	0.34
Mean stem volume	3.46	1	**0.06**
Harvester trail length	0.06	1	0.80
Pine proportion	0.69	1	0.40
Computed mean stem volume	3.59	1	**0.06**
Forest Origin	0.04	1	0.83
Harvested volume per hectare	0.01	1	0.93
Terrain Structure	1.20	1	0.27

Independent variables were removed one at the time from Model B. For each variable removed, the new multivariate model was compared to the previous version, ensuring that the new model AIC was lower than the previous one.

Model C had the lowest AIC (Table 15), although the only variable which had statistical significance throughout the process was the variable "Month". Removing any of the non-significant variables created a higher AIC. Additionally, AIC is merely a method of model fitting, not accuracy, which is why non-significant covariates were kept.

Table 15. Model C had the lowest AIC when predicting rutting. Model AIC = 253.36.

Independent Variable	LR Chisq	Df	Pr(>Chisq)
Spruce proportion	2.50	1	0.11
Deciduous species proportion	2.44	1	0.12
Month 2	42.71	11	<0.001
Harvested volume/ha	0.11	1	0.75

Step 4. A univariate model containing the only statistically significant covariate "Month 2" was combined with all statistically insignificant removed in Step 2 and Step 3. None of the new models had a lower AIC. However, some of the variables became significant. These models (presented in Table 16) were further processed during Step 5.

Table 16. Models D-E with new statistically significant variables after processing in Step 5.

Model	Variable	LR Chisq	Df	Pr(>Chisq)	AIC
Model D	Month 2	39,06	11	<0.001	268.41
Model E	Month 2	40,07	11	<0.001	263,05
	Spruce proportion	3,36	1	0.067	
Model F	Month 2	37,48	11	<0.001	263,56
	Obstructing undergrowth	2,85	1	0.091	
Model G	Month 2	36,95	11	<0.001	262,24
	Deciduous species proportion	4,17	1	0.041	
Model H	Month 2	40,51	11	<0.001	261,92
	Pine proportion	4,49	1	0,034	

Step 5. Models C and E-H were controlled for multicollinearity (Model D only had one variable) using the Variance inflation factor (VIF). Multicollinearity did not occur in any of the models. Results are presented in Table 17.

Table 17. Variance inflation factor (VIF) of multivariate models C, E, F, G and H.

Model Name	Variable	GVIF	Df	GVIF^(1/(2*Df))
Model C	Spruce proportion	1.20	1	1.05
	Deciduous species proportion	1.15	1	1.07
	Month 2	1.15	11	1.01
	Harvested volume per hectare	1.06	1	1.03
Model E	Month 2	1.09	11	1.00
	Spruce proportion	1.09	1	1.04
Model F	Month 2	1.02	11	1.00
	Obstructing undergrowth	1.02	1	1.00
Model G	Month 2	1.08	11	1.00
	Deciduous species proportion	1.08	1	1.04
Model H	Month 2	1.11	11	1.00
	Pine proportion	1.11	1	1.05

Step 6. None of the models were able to give an accurate prediction of rutting. None of the 16 rutting damages present in the test data were detected.

5.2. The Predictive Model – Severe Rutting

Step 1. The AIC-values from each univariate model is presented in Table 18. The AIC of the reference model was 467.6656, which was set as a threshold for inclusion of independent variables before proceeding to *Step 2.*

Table 18. AIC-values from each univariate model. All variables below the reference threshold is denoted with bold.

Variables Included	D.f	AIC
All	*	94
Zero	*1*	*467.67*
Obstructing trees proportion	2	**467.45**
District	21	475.27
Month 1	12	**443.59**
Spruce proportion	2	468.47
Obstructing undergrowth	2	468.44
Total harvested volume	2	**271.00**
Snow factor	2	**456.12**
Average forwarder load size	2	467.71
Deciduous species proportion	2	**458.74**
Terrain inclination (as factor)	31	496.45
Terrain inclination	2	**464.47**
Month 2	12	**438.51**
Mean stem volume	2	**466.50**
Harvest Unit area	2	467.70
Mean volume/ha reported by the harvester	2	**467.66**
Mean volume/ha reported by the forwarder	2	467.88
The total forwarding distance	2	**466.96**
Harvester trail length	2	467.77
Pine proportion	2	468.17
Computed mean stem volume	2	**466.60**
Forest Origin	2	**466.94**
Harvested volume/ha	2	**459.13**
Year	11	470.25
Terrain Structure (as factor)	31	505.32
Terrain Structure	2	**467.41**

Steps 2 and 3. The first model (Model 1) included all independent variables with an individual AIC lower than the reference AIC. The AIC of Model 1 was 444.8875, which is lower than the Reference AIC 467.6656 (Table 19).

Model 2 (Table 19) had the lowest AIC acquired during *Steps 2 and 3*. Model 2 had an AIC of 422.7791, although because not all covariates were statistically significant this was not chosen as the final/only model to be tested in *Steps 4-7*.

Table 19. Model 2, the model with the lowest AIC acquired during Steps 2 and 3. Model AIC=422.78.

Independent Variable	**LR Chisq**	**Df**	**Pr(>Chisq)**
Obstructing trees proportion	5.03	1	0.02
Snow factor	2.65	1	0.10
Deciduous species proportion	13.85	1	<0.001
Terrain inclination	6.01	1	0.01
Month 2	35.33	11	<0.001
The total forwarding distance	2.90	1	0.09

Model 3 (Table 20) was the final model of *Steps 2 and 3*, and although it did not have an AIC lower than Model 2, it contained solely statistically significant variables.

Table 20. Model 3, the final model of Steps 2 and 3, contains only statistically significant variables. Model AIC = 423.72.

Independent Variable	**LR Chisq**	**Df**	**Pr(>Chisq)**
Obstructing trees proportion	4.90	1	0.03
Deciduous species proportion	14.82	1	<0.001
Terrain inclination	8.03	1	<0.01
Month 2	43.54	11	<0.001

Step 4. Each of the variables removed in *Step 1* was brought back into Model 2. The variable "Harvester trail length" came close to statistical significance when added to Model 2. This generated Model 4 (Table 21) which proceeded to testing in *Step 5*.

Table 21. Model 4 generated from Model 2. Removed variable "Harvester trail length" tested for interdependence.

Independent Variable	**LR Chisq**	**Df**	**Pr(>Chisq)**
Obstructing trees proportion	3.96	1	0.05
Snow factor	2.51	1	0.11
Deciduous species proportion	15.57	1	<0.001
Terrain inclination	5.31	1	<0.001
Month 2	36.59	11	<0.001
The total forwarding distance	3.09	1	0.08
Harvester trail length	3.74	1	0.05

Same treatment was applied to Model 3, which generated Model 5 (Table 22).

Table 22. Model 5 generated from Model 3. Removed variable "Harvester trail length" tested for interdependence.

Independent Variable	LR Chisq	Df	Pr(>Chisq)
Obstructing trees proportion	3.84	1	0.05
Deciduous species proportion	16.53	1	<0.001
Terrain inclination	7.16	1	<0.01
Month 2	45.47	11	<0.001
Harvester trail length	3.71	1	0.05

Step 5. Models 2-5 were controlled for multicollinearity using the Variance inflation factor (VIF). Multicollinearity did not occur in any of the models. Results are presented in Table 23.

Table 23. Models 2-5, controlled for multicollinearity using the Variance inflation factor.

Model Name	Independent Variable	GVIF	Df	GVIF^(1/(2*Df))
Model 2	Obstructing trees proportion	1.16	1	1.08
	Snow factor	1.12	1	1.06
	Deciduous species proportion	1.13	1	1.06
	Terrain inclination	1.17	1	1.08
	Month 2	1.23	11	1.01
	The total forwarding distance	1.07	1	1.04
Model 3	Obstructing trees proportion	1.14	1	1.07
	Deciduous species proportion	1.13	1	1.06
	Terrain inclination	1.13	1	1.06
	Month 2	1.10	11	1.00
Model 4	Obstructing trees proportion	1.18	1	1.09
	Snow factor	1.11	1	1.05
	Deciduous species proportion	1.17	1	1.08
	Terrain inclination	1.17	1	1.08
	Month 2	1.27	11	1.01
	The total forwarding distance	1.07	1	1.04
	Harvester trail length	1.09	1	1.04
Model 5	Obstructing trees proportion	1.16	1	1.08
	Deciduous species proportion	1.17	1	1.08
	Terrain inclination	1.14	1	1.07
	Month 2	1.14	11	1.01
	Harvester trail length	1.09	1	1.04

Step 6. None of the models were able to give an accurate prediction of rutting. None of the Severe Rutting damages present in the test data were detected.

Neither the models for rutting or severe rutting detected any damages. However, neither did the model falsely assign any damages to the harvesting units. Figure 5 visualizes the probability of a damage occurring, compared to actual damages present in each harvest unit. Almost none of the observations had a probability above 0.5, and the one that did, did not have any actual damages.

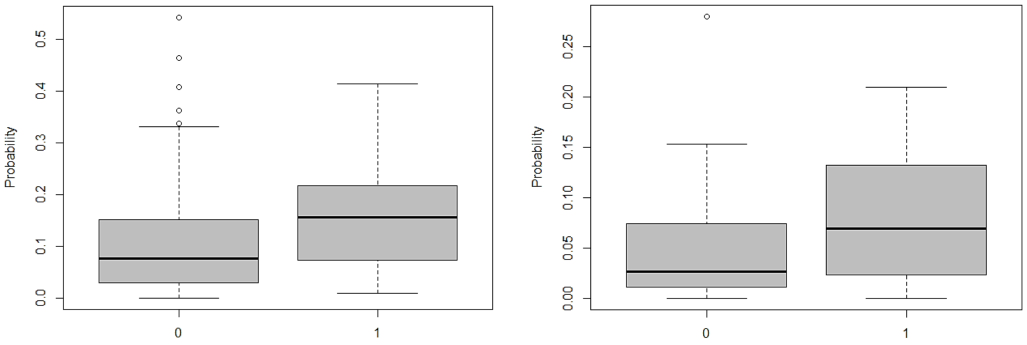

Figure 5. The probability of a damage occurring, compared to actual damages present in each harvest unit. Model C (rutting) to the left and Model 3 (severe rutting) to the right.

5.3. The Cost of Implementing a Service Guarantee

5.3.1. Assessment Sample Size

With data collected between years 2010-2019, the average number of damaged harvesting units each year was calculated. The total expected number of damages detected was assumed to be proportional to the *assessment sample size* and is presented in Table 24 and Table 25.

Table 24. Rutting damages per year and assessment sample size

Year	10 %	20 %	30 %	40 %	50 %
Total	***30***	***60***	***91***	***121***	***151***
2010	2	4	5	7	9
2011	3	6	9	12	15
2012	3	7	10	13	17
2013	3	6	10	13	16
2014	4	8	12	16	20
2015	4	9	13	17	21
2016	4	8	12	16	20
2017	4	7	11	15	19
2018	3	7	10	13	17
2019	5	9	14	18	23
Mean	***3***	***7***	***10***	***14***	***17***

Table 25. Severe rutting damages per year and assessment sample size

Year	10 %	20 %	30 %	40 %	50 %
Total	***54***	***109***	***163***	***217***	***272***
2010	3	7	10	13	16
2011	5	10	16	21	26
2012	6	12	18	24	30
2013	6	12	17	23	29
2014	7	14	21	28	35
2015	8	15	23	31	38
2016	7	14	21	28	35
2017	7	13	20	27	34
2018	6	12	18	24	30
2019	8	17	25	33	41
Mean	***6***	***13***	***19***	***25***	***31***

The average area (hectare) per year of each *assessment sample size* was also calculated using the harvested area from years 2010-2019 (Table 26).

Table 26. Assessment Sample Size area per year, expressed in ha.

Year	10 %	20 %	30 %	40 %	50 %	100 %
Total	***5 345***	***10 689***	***16 034***	***21 378***	***26 723***	***53 446***
2010	415	830	1 245	1 660	2 076	4 151
2011	627	1 253	1 880	2 506	3 133	6 265
2012	646	1 292	1 938	2 584	3 230	6 459
2013	621	1 242	1 864	2 485	3 106	6 212
2014	557	1 113	1 670	2 226	2 783	5 565
2015	671	1 343	2 014	2 685	3 357	6 713
2016	644	1 287	1 931	2 575	3 219	6 437
2017	576	1 151	1 727	2 302	2 878	5 756
2018	589	1 178	1 766	2 355	2 944	5 888
2019	800	1 599	2 399	3199	3 999	7 997
Mean	***614***	***1 229***	***1 843***	***2 458***	***3 072***	***6 144***

5.3.2. Soil Damage Recovery Management

The total cost of *Soil damage recovery management* was calculated for each *Soil damage recovery scenario* and is presented in Tables 27-29. Additionally, the forest owner compensation option was also calculated and included in each scenario. As a reminder, in the forest owner compensation option, 50 % of the severe rutting damages detected in tenures were not treated. Instead, a payout was issued to compensate the forest owner. To clarify, if a sample size of 10 % in Scenario 1 is chosen, the cost of soil damage recovery is 39 991 SEK/year. Given the same scenario and sample size, the forest owner compensation option would result in a yearly cost of 31 285 SEK/year.

Table 27. Scenario 1, 100 % of rutting damages are handled by a forwarder. Expressed in SEK/Year.

Assessment Sample Size	Cost	Forest Owner Compensation
10 %	39 991	31 285
20 %	79 982	62 571
30 %	119 973	93 856
40 %	159 964	125 142
50 %	199 955	156 427
100 %	**399 910**	**312 854**

Table 28. Scenario 2, 50 % of rutting damages are handled by a forwarder. Expressed in SEK/Year.

Assessment Sample Size	Cost	Forest Owner Compensation
10 %	45 209	36 504
20 %	90 419	73 008
30 %	135 628	109 511
40 %	180 838	146 015
50 %	226 047	182 519
100 %	**452 094**	**365 038**

Table 29. Scenario 3, 100 % of rutting damages are handled by an excavator. Expressed in SEK/Year.

Assessment Sample Size	Cost	Forest Owner Compensation
10 %	50 428	41 722
20 %	100 856	83 444
30 %	151 283	125 167
40 %	201 711	166 889
50 %	252 139	208 611
100 %	**504 278**	**417 222**

5.3.3. The Total Cost of Implementing a Service Guarantee

Since none of the models were able to predict soil damages, a simple mean was calculated from the detected damages each year and was used as cost calculation input. Each Soil damage recovery Scenario generated three different cost levels, depending on the Assessment labor type. In addition, each Soil damage recovery scenario was divided into two cost options, one where all damages were repaired, and one where forest owner compensation was applied to 50 % of the forest tenures. The total cost (SEK/year) of implementing the service guarantee is presented in Tables 30-35. In Tables 36-41 the cost is presented as an average cost divided by the total harvested volume (SEK/m3sub). In total, the cost of implementing the service guarantee ranges between 347 028 and 2 012 254 SEK/year, which is equivalent to 0.41 - 2.25 SEK/m3sub.

Two examples are provided to clarify how the tables are interpreted:

Table 30 represents the yearly cost of implementing the service guarantee, based on Scenario 1 (100 % of rutting damages are handled by a forwarder). The cost varies depending on the chosen employee type and assessment sample size. If an assessment sample size of 20 % is chosen, the total cost to implement the service guarantee per employee type is as follows: full-time 552 851 SEK/year, temporary 491 446 SEK/year and contractor 508 470 SEK/year. Through combining different employee types and assessment sample sizes, the total cost of implementing the service guarantee can be estimated. Table 31 is interpreted in the same manner and represents Scenario 1, although here the forest owner compensation has been applied to 50 % of the tenures. Both options are available for each scenario.

Table 30. Total cost of implementing the service guarantee, Scenario 1. Expressed in SEK/Year.

Sample Size %	Full-time	Temporary	Contractor
10	355 734	325 031	333 543
20	552 851	491 446	508 470
30	749 969	657 860	683 397
40	947 087	824 275	858 324
50	1 144 204	990 690	1 033 251
100	2 129 793	1 822 765	1 907 886

Table 31. Total cost of implementing the service guarantee when applying the forest owner compensation option. Scenario 1. Expressed in SEK/Year.

Sample Size %	Full-time	Temporary	Contractor
10	347 028	316 325	324 837
20	535 440	474 034	491 059
30	723 852	631 744	657 280
40	912 265	789 453	823 502
50	1 100 677	947 162	989 723
100	2 042 738	1 735 709	1 820 830

Table 32. Total cost/year of implementing the service guarantee, Scenario 2

Sample Size %	Full-time	Temporary	Contractor
10	360 952	330 249	338 761
20	563 288	501 882	518 907
30	765 624	673 516	699 052
40	967 960	845 149	879 198
50	1 170 297	1 016 782	1 059 343
100	2 181 977	1 874 949	1 960 070

Table 33. Total cost of implementing the service guarantee when applying the forest owner compensation option. Scenario 2. Expressed in SEK/Year.

Sample Size %	Full-time	Temporary	Contractor
10	352 246	321 544	330 056
20	545 877	484 471	501 496
30	739 508	647 399	672 935
40	933 138	810 327	844 375
50	1 126 769	973 255	1 015 815
100	2 094 922	1 787 893	1 873 015

Table 34. Total cost/year of implementing the service guarantee, Scenario 3.

Sample Size %	Full-time	Temporary	Contractor
10	366 170	335 468	343 980
20	573 725	512 319	529 344
30	781 279	689 171	714 707
40	988 834	866 023	900 071
50	1 196 389	1 042 874	1 085 435
100	2 234 161	1 927 133	2 012 254

Table 35. Total cost of implementing the service guarantee when applying the forest owner compensation option. Scenario 3. Expressed in SEK/Year.

Sample Size %	Full-time	Temporary	Contractor
10	357 465	326 762	335 274
20	556 314	494 908	511 932
30	755 163	663 054	688 591
40	954 012	831 200	865 249
50	1 152 861	999 347	1 041 907
100	2 147 106	1 840 077	1 925 199

Table 36-Table 41 are interpreted as above, although the total cost is presented as SEK/m^{3}fub.

Table 36. Total cost/m3sub of implementing the service guarantee. Scenario 1

Sample Size %	Full-time	Temporary	Contractor
10	0.42	0.38	0.39
20	0.65	0.57	0.59
30	0.88	0.77	0.80
40	1.11	0.96	1.00
50	1.34	1.16	1.21
100	2.49	2.13	2.23

Table 37. Total cost of implementing the service guarantee when applying the forest owner compensation option. Scenario 1. Expressed in SEK/m^{3}fub.

Sample Size %	Full-time	Temporary	Contractor
10	0,41	0,37	0,38
20	0,63	0,55	0,57
30	0,85	0,74	0,77
40	1,07	0,92	0,96
50	1,29	1,11	1,16
100	2,39	2,03	2,13

Table 38. Total cost/m3sub of implementing the service guarantee. Scenario 2

Sample Size %	Full-time	Temporary	Contractor
10	0.42	0.39	0.40
20	0.66	0.59	0.61
30	0.90	0.79	0.82
40	1.13	0.99	1.03
50	1.37	1.19	1.24
100	2.55	2.19	2.29

Table 39. Total cost of implementing the service guarantee when applying the forest owner compensation option. Scenario 2. Expressed in SEK/m^{3}fub.

Sample Size %	Full-time	Temporary	Contractor
10	0,41	0,38	0,39
20	0,64	0,57	0,59
30	0,87	0,76	0,79
40	1,09	0,95	0,99
50	1,32	1,14	1,19
100	2,45	2,09	2,19

Table 40. Total cost/m3sub of implementing the service guarantee. Scenario 3

Sample Size %	Full-time	Temporary	Contractor
10	0.43	0.39	0.40
20	0.67	0.60	0.62
30	0.91	0.81	0.84
40	1.16	1.01	1.05
50	1.40	1.22	1.27
100	2.61	2.25	2.35

Table 41. Total cost of implementing the service guarantee when applying the forest owner compensation option. Scenario 3. Expressed in SEK/m^{3}fub.

Sample Size %	Full-time	Temporary	Contractor
10	0,42	0,38	0,39
20	0,65	0,58	0,60
30	0,88	0,78	0,81
40	1,12	0,97	1,01
50	1,35	1,17	1,22
100	2,51	2,15	2,25

6. Discussion

To meet the rising environmental awareness in the forestry industry, forest companies have been determined to find strategies to mitigate damages caused by harvesting. Thus, many forestry companies are actively working towards implementing soil protection strategies. These strategies are closely linked to an increasing importance for forestry companies to be perceived as sustainable and trustworthy in order to gain market recognition.

The service guarantee is an established strategy to gain market recognition in many business areas but has not yet become adopted into the forestry sector. A service guarantee can be a powerful tool, not only to gain market recognition and attract new customers, but also to develop and improve performance standards. As the service guarantee is not yet an acknowledged concept of the forestry industry, there are few studies investigating the prerequisites needed to create a service guarantee for soil damages related to final felling. Hence, this study appears to be first of its kind.

In order to calculate the expected average number of soil damages each year, a predictive model was developed. While soil damage modelling has gained more attention over the last decades, the needed input data with enough detail and quality are often difficult to obtain. Therefore, it was investigated if data which are readily available to most forest companies could be used to build a model to predict the risk of soil damages.

Two different types of soil damages are recorded during post-harvest assessment, rutting and severe rutting. As described, a binomial logistic regression model was used to develop the model. A multinomial logistic regression model was also a possible option for the prediction modelling; however, it was argued that the increased number of model outcomes (dependent variables) would not have been beneficial in the statistical analysis because of the limited number of observed damages. While this argument is true, it was discovered later in the process that the multinomial logistic regression model would also have offered some valuable insight. Initially, it was not believed that it would be of interest to find out if there were harvesting units where both rutting and severe rutting was present. Because it was possible for both soil damage types to exist in the same harvesting unit, it was believed that the fourth model outcome would not be of any interest. It was later discovered, in the process of creating the *Soil Damage Recovery Scenarios,* that the cost of damage recovery management is dependent on the machinery relocation expenses. Meaning that, if a rutting and severe rutting damage is present in the same harvesting unit and are both handled by an excavator, the relocation expenses would be halved compared to the current calculations. It was not possible to examine this option within the given timeframe of this study, although it would be encouraged to incorporate this in future research.

The result of the current study indicates that the dataset is not suitable to create predictive models. There are several possible explanations for this result. One possible explanation is that the dataset was too small. While the number of unique observations included in the sample plot is normally considered to be a sufficient basis for interpretation, the percentage of observed soil damages in the dataset was relatively low. Hence the information basis for the observed damages becomes small. None of the predictive models succeeded in detecting Rutting or Severe Rutting. However, it is noteworthy that the model also did not falsely assign damages to harvesting units where damage was not present. This result further supports the idea that the dataset was too small (the number of damages were too few), and that a larger dataset could have provided a different result.

Other possible explanations could stem from the model building process. The method chosen for variable inclusion was Stepwise variable selection. It has long been debated whether this is the best approach to find important variables to include in a regression model (Flom, 2018). Some of the critique directed towards the method is that stepwise regression sometimes gives flawed results of values such as R-squared, chi-square and p-values. Another problem is that highly correlated independent variables are removed early in the model building process and have to be brought back again later. However, one argument which strengthen the use of stepwise selection is the possibilities to manage large datasets with many predictor variables in a systematic manner. Additionally, the systematic nature of the process itself can give valuable information about the independent variables.

Perhaps, the most plausible explanation is that the variables included in the study is not suitable for building prediction models, causing a correlation which is too weak to predict the risk of soil damages. Although it was not possible to predict soil damages, it was still possible to detect correlation between soil damages and a few of the variables included in the study. The detected correlation offered some insight into which contributing factors had the highest impact in causing severe soil damages.

Tree species composition had statistical significance in both prediction models, suggesting that this is an important factor regardless of soil damage severity. Tree species composition should logically mirror the conditions of the forest, given that the species composition is either natural or the suitable species have been established in the forest area. Three different variables representing species were available; variables “Deciduous species proportion”, “Pine proportion” and “Spruce proportion”. In the Rutting model they all became significant, which is not surprising since they all essentially describe the same thing. An increasing percentage of one tree species should naturally mean a lower percentage of another, which is why they should not be used together in the same model.

Terrain inclination was statistically significant (p=<0,01) in relation to Severe Rutting. This finding is consistent with that of Jourgholami et al. (2014), who investigated this correlation and found that forwarding uphill in 0-10% slope had great impact on bulk density, penetration resistance and total porosity. The result also reflects those of Shabani (2017), whom modelled soil damage caused by harvesting in Caspian forests (Iran) and found that slope degree and soil type had the highest influence on soil damages.

One unanticipated finding was that “Obstructing trees proportion” was statistically significant in one of the models predicting severe rutting. However, no such evidence was supported by previous research.

In reviewing the literature, several studies concluded that the works characteristics are highly influential factors when dealing with soil damages. Picchio, Mederski and Tavankar (2020) and Cambi et al. (2015) found that the forwarder load size had a positive correlation to soil damages. However, the findings of the current study do not support this statement. “Forwarder load size” was one of the variables where extreme outliers were found, which might affect the result. Additionally, this rather contradictory result may be due to the fact that “Forwarder load size” does not take the total weight of the machine into consideration. Cambi et al. (2015) stated, in consistence with Williamson and Nielsen (2000), that the weight of the vehicle had a significant role in contributing to soil damages after harvesting operations. The weight of the vehicle was not possible to include in this study, which adds a source of uncertainty. The weight of the vehicle should logically be correlated to the average forwarder load size. However, the forwarder load size can be adjusted in order to avoid soil damages in sensitive areas. This reasoning highlights one of the negative aspects of observational data.

Many other works characteristics were also not possible to include. An example of this is ground contact device, which positively influenced the existence of rutting (wheels cause highest risk of rutting, followed by bogie track and track) (Cambi *et al.*, 2015).

Picchio, Mederski and Tavankar (2020) also found that the design and yard logistics and forest road network characteristics had an impact on soil damage severity. This partly accords with the observations of the current study where "Harvester trail length" (p = 0.05) and "Total forwarding distance" (p = 0.08 and p = 0.09) had a slight correlation with severe rutting, bordering on the threshold of statistical significance.

Month of forwarding operations had the strongest statistical significance in both Rutting and Severe Rutting models. The variable month was assumed to mirror the weather conditions. Months with generally more precipitation and lower temperature should increase the moisture content which according to Hillel (1998), had the highest impact on the risk of soil damages. This finding broadly supports the work of other studies in this area. However, it is important to remember that the variable month is not a direct indication of soil hydrology. Weather conditions can vary between years, providing possibly different prerequisite conditions for harvesting each year. A difference between the two variables "Month 1" (First date of forwarding operations) and "Month 2" (Last date of forwarding operations) was detected, as the variable "Month 1" was never statistically significant in any of the models. It is difficult to explain this result, although one possible explanation could be that the last date of forwarding operations is more accurately reported by the machine operators, and therefore represent the actual time of management operations. Whereas the first date of forwarding operations, which is explained in the methods section, could to a larger extent mirror the date when the machine operator first opens the computer files to gain information about the upcoming task.

The variable "Year" was solely included as reference variable. The variable was incorporated into the models at an early stage solely to investigate if there would be a correlation between year of harvest and soil damages. The variable was not included further in the model building process as it is not possible to use as a prediction parameter. Detection of this strong correlation further motivates the inclusion of sample plots covering a 10-year timespan. Weather extremes and fluctuations balance each other out due to the long timespan, which creates a dataset representative of the average weather conditions.

"Forest Origin" is another variable which is strictly related to administrative traits. This variable was still an interesting candidate as a covariate of a predictive model. A generally accepted idea within the forestry sector is the perception that forestry companies are more careful when operating on tenures than on their own land. There are no such instructions conveyed to the forestry machine operators; the goal is to minimize the impact of forestry operations regardless of forest ownership. It is still likely that the customer-oriented mindset of the company causes extra precautionary measures in forestry tenures. The original hypothesis was therefore that there would be a higher percentage of soil damages on SCA's own forests. However, no such statistical correlation could be found, suggesting that the same precautionary measures are applied in all harvesting operations.

Some results of the current study match those observed in earlier studies, while others were not in line with existing body of literature. A note of caution is due here since comparing the results of this study with other studies within the field comes with a set of challenges. The definition of rutting and severe rutting in this study is created by SCA Skog AB. As mentioned in the background section, there are no general guidelines adopted by the entire forestry sector, so each company makes their own definitions. This creates challenges for comparison, not only in relation to results from the academic sector, but also between different companies.

In addition to the differences in defining soil damage, there is also a fundamental difference in the research approach. The current study is an observation study and the majority of the existing body of literature is based on experimental study designs. In observational studies, there is a potential bias from taking certain factors into consideration beforehand, which needs to be taken into consideration. For example, the forest company is unlikely to harvest in forests where the risk of soil damage is high. The positive aspect of the observational data is its increasing availability, but it also increases the risk of creating relationships between variables which are too complex and chaotic to measure (Wansink, 2019). This difference between observational data and experimental data creates a fundamental gap which makes them difficult to compare. For example, in this study one sample plot represents an entire harvesting unit. The harvesting unit can be of varying size and the data representing each unit is an interpolation of the varying characteristics of the entire unit. In an experimental study, the sample plot is usually a smaller area defined by homogeneous traits.

It was mentioned in Section 4 – Method and Materials, that "neither depth, length nor areal coverage of the soil damage is noted, the assessment simply states if there was soil damage present at the site or not". This adds another problem when comparing this study to other studies investigating soil damage and forestry interaction. These studies have normally denoted the severity and exact position of the ruts. Additionally, most experimental studies aims to isolate the factor of interest. Given the nature of this study, each factor does not have such prerequisites. An example is given to clarify. Cambi et al. (2015) found in several studies, that the terrain inclination combined with forwarding direction had a strong correlation with rutting. This is in line with the findings in this current study, where the variable "Terrain inclination" is suggested to have a positive and statistically significant influence on the presence of severe rutting. However, "Terrain inclination" represents an average inclination of the entire Harvest Unit. Which means that a high “Terrain inclination”-grade doesn’t specify if the entire unit has a particularly varying altitude, or if just parts of the harvesting units has this trait. To further elaborate, since the geographical location or extent of the rut was not recorded, it is not possible to establish if the soil damage happened in or in proximity to a high inclination area. While there is scientific evidence which suggests that soil damage is statistically more likely to appear in steep terrain, it is not possible to draw the same firm conclusion from the results of this study. The author of the present study will argue that it is likely that these will correlate but will not go further than that.

Another source of error is the existence of outliers. There was quite a bit of outliers detected during data processing. These were identified and removed by introduction of a maximum allowed threshold for inclusion. The maximum thresholds used in this study are subjects to criticism. Because the thresholds were set too high, data includes unrealistic values. The main motivation behind this reasoning was based on a fear of removing too much data from the dataset, as there already was many observations missing in the original dataset. In hindsight, a smaller dataset would have been preferred to a large dataset with many outliers. This means that there were flawed data in the dataset which could undermine the correlation effect and therefore affect the result. If given more time, it would also be valuable to investigate the factor generating the outliers more closely.

There is general consensus in the existing body of literature that soil moisture content and soil type are the most influential factors related to soil damages caused by harvesting (Hillel, 1998; Williamson and Neilsen, 2000; Cambi *et al.*, 2015; Shabani, 2017). However, these were not possible to include in the model, which is a significant weakness of the model. Although some of the variables, such as tree species composition and month can give an indication of these characteristics, it is an indirect variable which causes insecurities. The forest company and its contractors have the hydrological maps available during planning and on-site operations. However, there were no feasible way of quantifying the hydrological traits of the harvesting units during the time frame of this study.

Although I have directed some critique towards the nature and accuracy of the data included in the study, it is important to keep in mind that the objective of this study was to identify if the variables readily available to SCA Skog AB could be used to create a predictive model. Hence, it is motivated to also include variables with less scientific credibility, even though the interpretation of said data needs to be carried out with some precaution. I would also like to stress that this is the kind of information available to most forest companies. While the ideal situation would be to have as detailed information as possible about the forest area, this is rarely the case. Forestry companies base their decisions on the best information possible, meaning the kind of information which is obtainable through maps and field visits.

The results of this study suggest that available data can be used to detect and analyze trends, however they are not sufficient for actual predictions.

As it was not possible to predict the risk of Rutting and Severe Rutting, an average was calculated to provide the expected number of soil damages detected each year. Thus, the question to calculate cost estimate intervals for a guarantee was fulfilled. It is important to note, that the calculated mean is based on a sample which was treated as a completely random sample in order to carry out statistical analysis. However, since the sample more closely resembles a convenience sample, where higher risk harvesting units have been targeted, the result is likely to be overestimated.

Depending on the chosen *Soil Damage Recovery Scenario, Assessment Sample Size, Employee option and Service Guarantee Payout,* it was concluded that the implementation cost of the service guarantee should range between 347 028 and 2 012 254 SEK/Year, which would be equivalent to 0.41 – 2.25 SEK/m^3sub.

The cost interval should be viewed as a suggestion for future implementation of the guarantee. The guarantee is one strategy of connecting a monetary value to the consequences of increased soil damage, and to highlight the monetary gain of precautionary improvements.

Certain parameters are likely to change slightly. For example, the assessment sample size was assumed to be proportional to the number of detected damages. However, in future implementation it is recommended that the sample is directed towards harvesting units with higher risks, in order to detect as many damages as possible without increasing the cost. This also goes in line with the recommendations of the service guarantee which is presented in the background section. The guarantee is a tool of inspire trust in the company, and it is not desirable that the customer/forest owner needs to invoke the guarantee themselves. However, if the forest owner detects the damages themselves, this will also affect the cost of implementing the service guarantee. Suggesting that the cost of the service guarantee is not only dependent on the decisions of the company, but the expected customer behavior also needs to be factored into the equation. In order for the company to be perceived as trustworthy, the field personnel also need to portray the same competence. It was detected during data processing that some harvesting units had been assessed several times by different personal, with different outcomes. This was not a common source of error, but still suggests that there are room for interpretation in the assessment which causes errors. Assessment inconsistency can cause serious problems in the entire process and could possibly be the root cause behind the models' inability to predict soil damages. It is therefore suggested that field personnel are offered education and calibration regularly.

As the discussion focuses heavily on critiquing the methodology and the dataset, it raises intriguing questions regarding the prerequisites needed in order to enable practical implications of the service guarantee for soil damages related to mechanized harvesting. This study appears to be first of its kind which is why I state that these findings contributes with a positive achievement to the field.

Some of the issues emerging from this study could provide insight into future development needs of the service guarantee. Thus, it is recommended for future research and improvement that definitions of rutting and severe rutting are standardized, to enable comparison. This would not only create an opportunity to put this study in a wider research context but would also increase the opportunities for communication between forestry companies in the sector. After all, this service guarantee is just one of many steps in the attempt to create a more qualitative and gentle forest management. Not just at SCA but in the entire forestry sector. It is also recommended that available data is processed more thoroughly in order to avoid outliers affecting the result. Future research should also look to include other variables available, in order to accurately predict soil damages and create a true and representative service guarantee.

7. Conclusions

This project was undertaken to investigate the prerequisites of creating a service guarantee for soil damages. In this investigation, the aim was to assess the possibilities to create a predictive model based on variables readily available to forest companies, and to use the model result as an input to calculate the cost of implementing the service guarantee. The result of this investigation shows that the current dataset is not suitable to create predictive models. Although it was possible to detect correlation between the independent variables, and rutting and severe rutting, it was not strong enough to be used in a prediction model. Hence, current variables cannot be used as a tool to predict costs in a service guarantee.

As it was not possible to predict the risk of Rutting and Severe Rutting, an average was calculated to provide the expected number of soil damages detected each year. Thus, the second aim, to calculate cost estimate intervals for a guarantee was possible to fulfill. Depending on the chosen *Soil Damage Recovery Scenario, Assessment Sample Size, Employee option and Service Guarantee Payout,* it was concluded that the implementation cost of the service guarantee should range between 347 028 and 2 012 254 SEK/Year, which would be equivalent to 0.41 – 2.25 SEK/m^3sub.

The main weaknesses in this study lies in the accuracy of the data and decisions made during data processing. Due to extreme outliers, the available data needed extensive processing in order to be used in any practical sense. If the outliers are caused by a systematic flaw in the data, then that might be the actual reason behind the result and needs to be addressed by the company. Extensive datasets are needed in order to have enough damages to derive information from, however this extensive dataset is not feasible to process during the timeframe of the study. This contradiction is problematic in deriving a representative result.

This present study appears to be the first study to provide a comprehensive assessment of combining a predictive model for soil damages with the framework of a service guarantee. In spite of its limitations, the study adds to the understanding of the complexity in predicting soil damages and creating a realistic and representative service guarantee for soil damages in a large Swedish forestry company.

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