Harvesting in the Boreal Forest on Soft Ground

Ways to reduce ground damage

Jeanette Edlund
Faculty of Forest Sciences
Department of Forest Resource Management
Umeå

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Harvesting in the Boreal Forest on Soft Ground: Ways to Reduce Ground Damage.

Abstract

The overall aim of the studies underlying this thesis has been to acquire knowledge relating to potential methods of reducing both the amount and severity of ground damage caused by forest machinery used in the boreal forest. The work focused on technical solutions applied to the forwarders that had the potential to reduce ground damage such as rutting and soil compaction. Additionally, the work focused on detecting areas that had a weak bearing capacity, using terrain indices based on digital elevation models and pre-existing forestry register data.

In paper I, it was shown that by combining forestry register data and terrain indices to find the Rammsonde pressure on till soil**,** 73% of the measurements correctly classified low or high bearing capacity ground.

In paper II, a forwarder with individually steerable wheels was described that**,** compared to a conventional forwarder, formed shallower ruts when driving in a straight line on forest land and made narrower ruts when turning on both forested land and arable land. When driving in a straight line on soft soil with or without load, the ruts from the conventional forwarder were shallower.

In paper III, simulations showed that the new Long Track Bogie (LTB), with a bearing capacity dependent contact area, negotiates low obstacles more smoothly than a conventional bogie and can handle wider ditches. The soil displacement from the LTB is also smaller when turning. In live tests on firm ground, the mean towing force for the LTB was 62% higher than for the conventional bogie and the rolling resistance was higher for the conventional bogie compared to the LTB (paper IV).

The results indicate that it is possible to reduce ground damage when harvesting by developing forest machines with steering and transmission drive systems that minimize damage on both soft and firm ground and by developing planning tools that predict the soil bearing capacity at the stand level. This might allow a classification of the ground without visiting the forest site and thus facilitate the choice of appropriate forest machines.

Keywords: Soil damage, bogie, rutting, forest planning, forest machines, steering system, terrain indices, ground classification

Author's address: Jeanette Edlund, Department of Forest Resource and Management,
SLU/Sveaskog, Kolmilavägen 17, SE-941 86 Piteå, Sweden
E-mail: jeanette.edlund@ sveaskog.se

Contents

List of Publications

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

I Edlund, J., Grabs, T. & Bergsten, U. Can soft ground be predicted from terrain indices and forest registry data in a boreal landscape during early summer? *Submitted manuscript*.

II Edlund, J., Bergsten, U. & Löfgren, B. (2012). Effects of two different forwarder steering and transmission drive systems on rut dimensions. *Journal of Terramechanics, In Press*.

III Edlund, J., Keramati, E. & Servin, M. A long-tracked bogie design for forestry machines on soft and rough terrain. *Submitted manuscript*.

IV Edlund, J., Bergsten, U. & Arvidsson, H. A forest machine bogie with a bearing capacity dependant contact area: effects on acceleration, angular orientation when passing an obstacle and on towing force. *Manuscript.*

1 Introduction

The forestry industry in Sweden started in the middle of the 19th century when saw mills became one of Sweden’s most important industrial assets (Jäghagen and Sandström 1994). Axes and saws were the main tools used for felling. Horses were used to transport timber over short distances until as late as the 1950s and rafting was used for longer distances until as recently as the end of the 1960s.

In the 1960s, motorized vehicles were introduced on a large scale into forestry (Enström 1996). Since then, ground damage has become a significant problem. The early haulage machines, such as tractors, were used for many purposes including the harvesting and transporting of timber, but were often not suitable (Wästerlund 1989). In modern forestry, there are specialized machines for nearly every kind of activity such as scarification, planting, thinning, final harvesting and forwarding. Current machinery is smaller and better adapted for thinning operations than that which was available in the early days of mechanization (Wästerlund 1989). However, in recent years, the need for higher productivity has led to a slow but significant increase in machine weight.

Recently, some further general trends have become important. Public attitudes are becoming increasingly critical of environmentally dubious practices and more demanding of standards such as sustainable and environmentally sensitive production (Poršinsky, Pentek et al. 2012), for which certificates, such as the FSC or PEFC, can be awarded to forestry enterprises. The regulations governing these certificates include statements concerning ‘soil protection’ (Ziesak 2003). In 2000, the European Union formulated new policy initiatives under the Water Framework Directive, which relate directly to the acidification of surface water. Under this policy, any damage that affects water (such as mud and chemical contamination as a result of rutting), must be repaired within 15 years of the damage occurring (European Parliament 2000).

Therefore, amongst other factors, it is important that consideration to the environment is given when harvesting and transporting timber from the forest. The bearing capacities of the ground have a major effect on the amount and severity of ground damage. Therefore, the ground pressure of the machine used is very important (Poršinsky, Pentek et al. 2012). Choosing the right machine for a stand and the correct placement of the strip roads can be the difference between no ground damage and severe ground damage.

1.1 Climatic and spatial aspects

Meteorological models have shown that there has been a rise in the mean temperature of the earth (SMHI; Mellander, Laudon et al. 2007). This can affect the boreal forest in both positive and negative ways: some parts of the planet will become drier while some will become wetter. However, predictions of the future weather in Sweden say that the temperature will rise, but also that it will be wetter than at present (SMHI 2012). The variation on how the rise in mean temperature will affect the future weather in the boreal forest zone might be big. The risk of decreased bearing capacity as well as the risk of ground damage in the boreal forest is increased with these kinds of climatic changes.

Shorter winters lead to shorter periods when the ground is frozen. These periods have, for a long time, been used to harvest stands located on ground with very low bearing capacity. These are stands where the potential for harvesting is extremely low during unfrozen conditions. This might lead to a number of stands that cannot be harvested without causing ground damage unless there are winters that are cold enough to freeze the ground. Since the industry requires fresh raw material all year round (Ziesak 2003), this situation has increased the need to find new solutions to reduce ground damage during harvesting.

1.2 Types of ground damage and effects on environment

There are several types of ground damage, such as damage to the roots of living trees, which can reduce the growth rates of the remaining trees after thinning (Wronski and Murphy 1994). Roots increase soil strength considerably (Wästerlund 1989). Mechanical damage to tree roots caused by machines used in thinnings can result in loss of growth, decreased soil stability along with increased risks of root rot among the remaining trees. These risks are high in Nordic countries, especially in spruce stands since their roots lie close to the soil surface (Magnusson 2009).

Soil compaction is another type of damage that increases soil density. Subsoil compaction is a severe problem, mainly because its effects are long-lasting (more than three years) (Alakukku 1996). Compacted soil can cause a reduction in the growth of trees remaining after thinning and in the subsequent forest crop after final felling of up to 50%. This reduces the value of the wood when harvested (Eliasson and Wästerlund 2007), but as the stand is scarified after a final felling, thus loosening the surface soil before planting the next crop, any negative effects on growth from soil compaction are probably reduced (Wästerlund 1992). The effect of soil compaction seems to be greater on less fertile sites (Bygdén and Wästerlund 2007). It can be caused, for example, by increasing the number of forwarder passages, a process which correlates to a significant increase in soil dry density (Eliasson 2005).

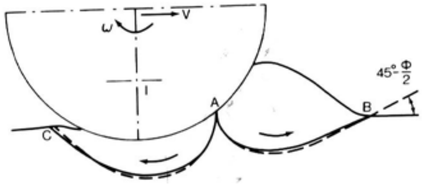

Figure 1. The bow wave in front of the tyre (Bygdén and Wästerlund 2007)

The other factors, apart from the weight of the vehicle, that affect soil compaction include soil movement from the bow wave generated by a rotating wheel (Figure 1). This wave rotates the soil particles first forwards and then backwards, thus changing the orientation of soil pores and reducing pore space (Bygdén and Wästerlund 2007).

The risk of subsoil compaction is highest when wet (i.e. weak/soft) soils are subjected to traffic with high wheel loads transmitting a moderate to high ground contact pressure. Soil wetness decreases the bearing capacity of the soil and higher wheel loads increase the depth to which stresses are transmitted within the soil (Poršinsky, Pentek et al. 2012), thus affecting a greater soil volume. The contact pressure itself has only a marginal effect on the stresses deep within the soil (Bygdén and Wästerlund 2007), but according to Greacen and Sands (1980), shear stresses from wheels also contribute to the compression of the soil. Subsoil compaction is detrimental to many properties that affect a soil's workability, as well as to drainage, crop growth and the wider environment. For example, subsoil compaction increases surface run-off (Greacen and Sands 1980) and topsoil erosion by impeding water filtration (Fullen 1985).

Rutting is another problem affecting both recreational use and water run-off. Rut depth is not significantly affected by tyre pressure, but does increase significantly with the number of machine passages (Eliasson 2005). According to Bygdén et al. (2003), rut depth caused by a loaded trailer is significantly affected by ground contact and soil type and is deeper than that caused by an unloaded trailer. Soil erosion and particle transport to streams are additional problems arising from soil damage. When soil is laid bare in ruts or wheel tracks, rain and surface water can then erode the soil more easily, especially where there are steeper inclines. The risk of erosion also increases with greater compaction of the soil (Magnusson 2009) as this increases the amount of water in the uppermost 10 cm of the soil and, generally, the water content increases with the number of passages of forestry machines (Figure 2, (Eliasson and Wästerlund 2007)).

Figure 2. Examples of rutting in a thinned area, from Bygdén & Wästerlund 2007.

Negative effects on water-based ecosystems are primarily caused by suspended particles, which alter the light levels within water bodies, thus affecting photosynthesis; in addition, these particles settle out and bury water-borne organisms. Other effects include the loading of water bodies with phosphorous and nitrogen causing eutrophication (Magnusson 2009), which can have serious consequences for the productivity of aquatic ecosystems.

Another big problem caused by soil damage is the increased mercury content of forest streams and lakes. The problem originates from the long-term spread of gaseous mercury throughout the atmosphere. Mercury subsequently concentrates in the organic surface layer of forests due to its tendency to bind very strongly to organic matter. In wetlands, where a lack of oxygen in the water is common from time to time, some of the leached mercury can form methyl mercury, which can then accumulate in living organisms such as fish, where it can reach harmful levels. Rutting and soil compaction, by increasing the run-off to streams and lakes, can simultaneously increase the amount of mercury in aquatic ecosystems (Magnusson 2009; Tjerngren 2012).

1.3 Critical time periods and sites

During the winter, whether the ground is frozen or not, the presence of snow and ice can have an important influence on the ability of humans to work in some terrains (Knutsson 2001; Suvinen and Saarilahti 2006). Areas that normally do not have the bearing capacity required for harvesting can be accessible during the winter when the ground is frozen. On the other hand, areas that normally have high bearing capacity can be inaccessible during thawing (Knutsson 2001) because the ground thaws from the top, creating a soil layer with high water content above a layer of frozen ground. The bearing capacity then stays low until all the ground has thawed and can drain freely (Knutsson 2001; Whitlow 2001).

The freezing process of the ground depends on several factors including the soil surface energy balance, the water content and the heat coefficient of the soil. Other important factors are soil type and snow depth (Knutsson 2001). The amount and timing of snowfall can have a significant effect on soil frost since the thickness of snow cover greatly influences the energy exchange at ground level (Sharratt, Benoit et al. 1999). Heavy snowfall in the early winter can prevent the development of a deep frost because it provides an insulating layer of snow (Hirota, Iwata et al. 2006). Thawing can counteract soil compaction, the biggest problem with wet ground should thus be soil displacement and rutting, whilst soil compaction per se is a minor problem.

The bearing capacity is dependent on the moisture content in the soil, but also on the soil type. There are certain sites that are extremely vulnerable to ground damage, such as mires and areas close to lakes or streams. These areas can be weak, but additionally, the ground damage can also be severe since the surrounding water can be affected.

In some areas, ground damage such as rutting has a limited effect on the surrounding environment, rutting from a forest machine on areas not joined to water being an example (Berg 2011). This kind of ground damage might not affect the environment, but the area might not be as attractive for recreational purposes since it has less aesthetic appeal.

1.4 Measures to reduce soil damage

There are several methods and tools that can be used to improve accessibility to soft ground and minimize soil damage. These methods and tools are often expensive to use and move. In many harvesting operations, logging debris i.e. branches and tree tops, are used to reinforce strip roads in stands (Hallonborg 1982), which results in a substantial increase in soil bearing capacity (Wronski, Stodart et al. 1989), reduced rutting (Hallonborg 1982;

Wronski, Stodart et al. 1989) and reduced soil compaction (McDonald and Seixas 1997). According to Eliasson and Wästerlund (2007), slash reinforcement of the strip roads significantly reduces the change in soil dry density and soil porosity that would otherwise occur in the upper 20 cm of the soil. They showed that a thin slash cover (10 cm) gives less protection than a thick one especially after multiple passes. The major effects of slash seem to occur in the upper soil layer, which is the most important layer for spruce tree growth (Wronski and Murphy 1994). However, in the Nordic countries**,** during the last decade, there has been increased interest in using this logging debris for energy production. If these logging residues are to be used for energy production it will not be possible to use them for reinforcement of strip roads (Eliasson 2005). According to Eliasson and Wästerlund (2007), it would be worthwhile reinforcing strip roads with slash on certain parts of clear-cuts, even if the slash would otherwise be harvested for energy use, because of the economic benefits of reducing soil compaction in the topsoil by slash reinforcement.

Methods that reduce the risk of soil disturbance include using larger tyres, lower tyre pressures and bogie tracks (Alakukku, Weisskopf et al. 2003; Chamen, Sherwin, Owende et al. 2004).

Myhrman (1990) reported that an increase of the tyre width from 600 mm to 800 mm reduced rut depth by approximately 50% for an eight-wheeled, 22 tonne forwarder. Even though increased tyre diameter and tyre width effectively decreases the ground pressure, there are some limitations since excessively wide tyres would require too much space for a European-style thinning operation (Wästerlund 1992). Using wider tyres and bogie tracks are not always enough to avoid ground damage even though they have benefits.

According to static loading theory, a rectangular contact area is better than a circular one of the same area, since it will engage with a bigger soil column (Bygdén and Wästerlund 2007). By using bogie tracks**,** a long rectangular-shaped contact area can be achieved. The rut depths for a vehicle equipped with bogie tracks are decreased by 30 – 40% compared to a vehicle with 700 mm tyres without tracks. Bogie tracks have also been considered to improve mobility, especially on wet soils (Bygdén and Wästerlund 2007). In weak, uniform soil conditions, vertical soil displacement and strain are significantly smaller with a bogie track compared to wheels at either normal or half-inflated pressure (Ansorge and Godwin 2007). Compared to wider and softer tyres, tracks on the bogie reduce rutting by up to 40% and reduce the cone index in the ruts by about 10%, although the tracks increase the mass of the trailer by 10 – 12% (Bygdén, Eliasson et al. 2003).

However, the use of bogie tracks has the drawback of shearing the upper part of the soil when turning the machine and has been considered to cause extra rolling resistance. Damage to the ground is reduced when longer and wider bogie tracks are used. On the other hand, large bogie tracks can be a disadvantage when driving in dense stands with narrow passages (Bygdén and Wästerlund 2007).

In recent years, forest machines equipped with multiple bogies and caterpillar tracks have been used (Poršinsky, Pentek et al. 2012). There are some forest machines that use bogies that allow longer tracks (Timbear (Anon 2012), Ponsse Wisent 10w, ProSilva 810T) (Kärhä and Poikela 2010). Even excavators have been used and forwarders/harvesters with caterpillar tracks have been used recently (Poikela 2011; Uusitalo, Ala-ilomäki et al. 2011) to reduce the damage on soft ground (Kärhä and Poikela 2010).

Low-pressure tyres are an established way of reducing soil compaction in agriculture (Alakukku, Weisskopf et al. 2003). According to Eliasson (2005), there was no significant effect of tyre pressure on soil compaction in a forestry study, but the interaction between the number of forwarder passes and tyre pressure was only marginally non-significant. This can be partly explained by the fact that compared to low tyre pressures as used in agriculture i.e. at or below 100 kPa, the lowest tyre pressures studied by Eliasson were all higher than 300 kPa. These high pressures are needed because of the high wheel loads and the uneven forest terrain, with stumps and stones that can damage the tyres (Trelleborg TwinForestry 2004). On primary strip roads, which are subject to a large number of forwarder passes, soil compaction cannot be avoided by reducing tyre pressures. However, on secondary strip roads, which are not driven on more than once or twice by a forwarder, reduced tyre pressures might limit soil compaction to a similar level caused by a harvester (Eliasson 2005).

The path width of any disturbance depends on the operating characteristics of the vehicle. A vehicle carrying out sharp turns will disturb a larger width of soil than a vehicle travelling in straight lines or carrying out smooth turns (Ayers 1994).

Temporary bridges or mats of pulp wood can be built for machinery movement over areas with low bearing capacity. For further reinforcement, slash can be placed on top of the temporary bridge. Material that has been used in the bridge is often too contaminated for use by the pulp industry and sawmills (Staland and Larsson 2002). Transferable wooden duckboards are another option for ground reinforcement. These are built from wooden sections that the forwarder places in front of each bogie (Staland and Larsson 2002).

Soil damage can still occur despite taking measures to increase the bearing capacity. Some damage can be repaired with an excavator, but these repairs are mostly cosmetic, since the soil will be susceptible to erosion for some years after the intervention (Staland and Larsson 2002).

An approach to decrease ground damage is to place the strip roads on the ground with the highest bearing capacity within a forest stand. In other words, driving on soft ground is avoided, which means that, in some cases, a detour is necessary. Soft areas are often characterized by relatively high soil moisture levels (Hummel, Ahmad et al. 2004) among other factors.

Even if you use the technical solutions and aids available today, it is still difficult to completely avoid damaging the soil. The available equipment is simply not good enough.

1.5 Determination of actual bearing capacity

The ultimate bearing capacity is defined as the intensity of pressure at which the supporting ground is expected to fail due to shearing (Whitlow 2001). Ultimate bearing capacity is usually calculated for the foundations of buildings. Therefore, you need to treat the forest soil as a foundation, even though it is not uniform and consists of things other than soil such as stones and roots. To calculate the bearing capacity you need to know the undrained shear strength of the soil, the width and the length of the foundation, the effective unit weight beneath the foundation base within the failure zone, effective soil or surcharge pressure at the foundation depth plus dimensionless bearing capacity factors and dimensionless correlation factors for cohesion. To collect all those data, a large number of both laboratory and in situ tests are needed (Gideon 1992). Therefore, an easier method to estimate the bearing capacity is through studies at numerous sites.

1.6 Existing classification of bearing capacity

In some cases, it is easier to evaluate the bearing capacity than to calculate it. A machine’s sinkage in the ground can be calculated depending on soil type and the ground pressure produced by the machine (Zeleke, Owende et al. 2007). A classification can be done from this model, if an acceptable level of sinkage is chosen. Another way of classifying the ground has been suggested by Uusitalo et al. (2011), where the forest ground can be classified by shear modulus where class 1 is scarce (20 – 30kPa), class 2 is moderate (30 – 40 kPa) and class 3 is substantial (50 – 60 kPa). Harvesting machines could then be chosen accordingly. Shear modulus, or modulus of rigidity, is the slope of the shear-stress/shear-strain curve. A similar classification has also been made by Törnqvist (2011) but here, the boundaries between the classes are set to < 40 kPa, > 40 kPa and > 50 kPa.

The Rammsonde pressure (RP), like the cone index, is not only dependent on shear strength, but also on the stiffness characteristics of the soil (Rohani and Baladi 1981). The RP is the force per square metre needed to penetrate the soil with a probe. This force (F_z) can be described by normal and shear stress according to the following equations:

Equation 1

Equation 2

L = height of the cone
σ = normal stress
α = half the apex angle of the cone
τ = shear stress
η = penetration depth

This means that the correlation between RP and shear modulus can be calculated and machines that have been classified according to shear modulus can be converted to RP given that the shear and normal stresses are known.

1.7 Forest machines and bearing capacity

The boreal forests in the Nordic countries are diverse and thus have different bearing capacities. Therefore, there are machines that are more suitable than others for each forest site. On sites with high bearing capacity and large trees, a large machine can be used without causing ground damage. A large machine is suitable since a machine that can transport a heavy load increases the productivity of harvesting. On weaker areas, it can be more suitable to use a lighter machine with lower ground pressure.

According to Andersson (2010), the bearing capacity of the ground can be divided into three groups. The first group consists of ground with sandy and gravel moraine which can withstand a forest machine that exerts a ground pressure in the range of 80 – 100 kPa without damaging the ground to an unacceptable level. The second group can withstand a loaded forwarder exerting 40 – 80 kPa of ground pressure and is made up of ground consisting of fine sand and silt. The last group, which consists of peat, can only withstand forest machines that exert a ground pressure below 40 kPa.

Of course, there are other factors affecting the overall bearing capacity such as the number of passages, the type of bogie used, if bogie tracks are used or not etc.

Table 1. Recommended ground pressure for different types of soil. The table also shows examples of forwarders that exert a ground pressure within the recommended range for each type of ground (Andersson 2010).

Type of ground	Recommended ground pressure	Example of forwarder
Sand and gravel moraine	80 – 100 kPa	John Deere 1710 Valmet 890.3 Ponsse Buffalo
Fine sand and silt	40 – 80 kPa	John Deere 1110 John Deere 1710
Peat	< 40 kPa	Bullmarksvagnen

In summary, since the rise of the mean temperature has reduced the time when the ground is frozen, the need to increase the bearing capacity of forest machines has become more and more important. The measures to reduce ground damage, such as using logging debris as ground reinforcement, bogie tracks, CTI and temporary bridges of pulp wood or transferable wooden duckboards are not enough. These aids are costly and make the forwarding more time-consuming. Therefore, more research is needed to find ways to avoid ground with a weak bearing capacity and to improve forest machines by decreasing their ground pressure and reducing ground damage.

2 Objectives

The overall aim of the studies underlying this thesis was to acquire knowledge relating to potential methods for the reduction of both the amount and severity of ground damage caused by forest machinery used in the boreal forest. The work focused on technical solutions applied to the forwarders that could, potentially, reduce ground damage such as rutting and soil compaction. Additionally, the work focused on how to detect areas that had a weak bearing capacity by using terrain indices based on digital elevation models and pre-existing forestry register data for the stands. In the longer term, this might allow a classification of the ground without visiting the forest site and thus determine the choice of appropriate forest machines.

Therefore, the approach presented in this thesis and applied in the underlying studies is of an interdisciplinary nature, involving forestry techniques as well as simulations.

More specifically, the objectives were to:

- Examine whether forestry register data relating to forestry terrain and site classifications, together with terrain indices (calculated from high resolution DEM) based on laser scanning, could be used to predict soil bearing capacity during the critical early summer period.
- Analyse whether these predictions were accurate enough to create guidelines for planning the location of strip roads to handle variations in bearing capacity.
- Compare rut formation (depth and width) between forwarders with different transmission drive systems for soils with different bearing capacities.
- Provide numerical evidence for the proposed features of the new Long Traction Bogie (LTB) with a bearing capacity dependent contact area and find the optimal choice of LTB design (e.g. angle of bogie frame and wheel diameters).

- Test two different bogie movements, the LTB and a conventional bogie, in the field to determine their respective abilities to negotiate obstacles such as steps and ditches and the smoothness with which the obstacles are passed.
- Investigate the towing force and rolling resistance on firm ground for the LTB and a conventional bogie.

3 Material and Methods

3.1 Experimental design

Paper I: Numerous data were collected for 161 evenly distributed points across the Krycklan catchment area (Figure 3). Forestry register data were collected at stand level, representing the stand where the measuring point was located. Soil moisture and RP data were collected to represent a small area with an approximate radius of 2 metres, centred on the measuring point.

Paper II: Data were collected from two study sites, one on soft arable land and one on intermediate forest land. Three machines were tested: a conventional forwarder without bogie tracks, a conventional forwarder with bogie tracks and a forwarder with individual steering of each wheel and a steering system that allows the wheels to follow the same tracks. The machines were tested both loaded and unloaded. Rut formation was measured along the ruts produced by the machines tested. Each machine drove in the same ruts up to 10 times; rut depth was measured, if possible, after 1, 2, 3, 4, 5, 8 and 10 passages. On arable land, the machines were first tested whilst driving in a straight line, then around an S-shaped course and in a circle with full swing. Replicate measurements were made within tracks. On forest land, a block design was used. Three blocks were made where each machine drove in a straight line and in a circular course with full swing.

Paper III: All the data were collected using a computer simulation.

Paper IV: Block design was used for both collecting data from acceleration measurements and for the towing force measurements. Two machines were tested, one conventional forwarder with a conventional bogie with bogie tracks and one forwarder equipped with an LTB with bogie tracks.

Two high obstacles (0.1 m, 0.2 m) were negotiated whilst measuring acceleration and angular orientation, once with both sides of the machine passing simultaneously and once with only one side passing the obstacle. Two ditches (1 m and 1.5 m wide) were also driven over – on one bogie side - with each machine. Five repetitions were made. When measuring towing force, three repetitions were made for each measurement. First, the towing force required to drag each machine with the gear box set to neutral was measured. After that, the towing force as a function of slip was measured.

3.2 Study Sites

The site considered for paper I was located in the forest around the Krycklan catchment area (Figure 3). Krycklan catchment is a forested watershed situated in the central boreal zone. The whole catchment is 68 km^2 (Ågren, Buffam et al. 2007). About 88% of the catchment area is forest land. The dominant soil type is morain and peat (Björkvald, Buffam et al. 2008). The Krycklan area is connected to Vindelälven (Vindeln river); water from Krycklan flows into Vindelälven approximately 5 km south east of Vindeln.

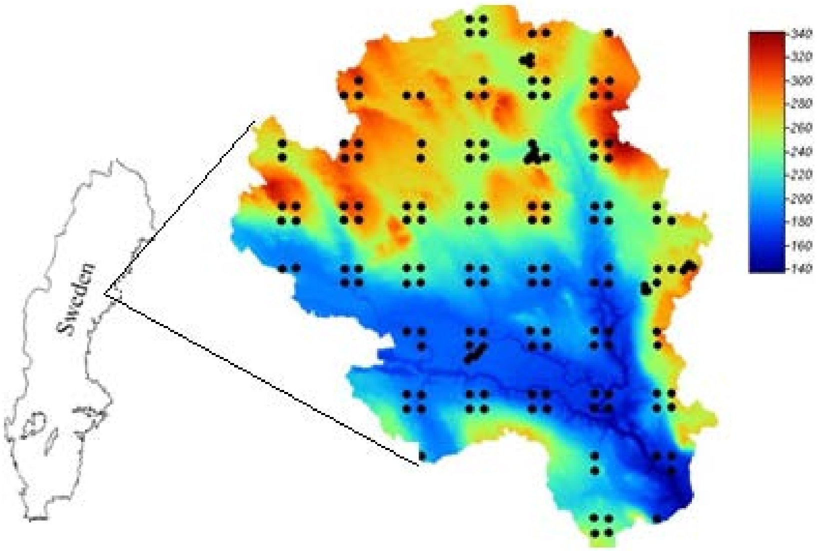

Figure 3. The Krycklan catchment area's location in Sweden and the 161 measuring points. The colour bar shows the altitude.

The forest component of the catchments is dominated by Norway Spruce (Picea abies) and Scots pine (Pinus sylvestris), whereas the mires are of ombrotrophic or oligotrophic minerogenic character and dominated by peat-forming Sphagnum species (Berggren, Ström et al. 2010). The height above sea level varies between 140 and 340 metres. The annual mean temperature is 1.7° C (1980 – 2008) and the mean precipitation over the year is approximately 600 mm (1981 – 2008), of which around 35% is snow (Laudon, Berggren et al. 2011). The forest became a research area in 1923; a field station and gauging station were built in 1979 when expanded climate measurements were started (SLU 2010).

The two sites considered in paper II were located in Uppsala community in central Sweden. The first test site was located on typical farmland approximately 10 kilometres from Tierp's city centre. The soil was originally an old lake bottom and primarily consisted of organic decomposed peat with a water content of approximately 38% by fresh weight. Since the soil is used to cultivate wheat during the summer, prior to the field study, the wheat was cut and removed. Therefore, there were dead roots from the wheat embedded in the soil.

The second test site was located on typical forest land approximately 25 kilometres northwest of Uppsala city centre, vegetated with mesic dwarf-shrub type flora. It had an intermediate forest soil with a higher bearing capacity than that found at the first site. It was classified as GYL 2,1,1, according to the Terrain classification for forestry work (Berg 1992). This classification means that it is possible to drive on the ground throughout the whole year, if caution is taken during thawing and heavy rainfall. The ground was fairly flat, with most obstacles being between 10 – 30 cm high with some more than 40 cm high. The slope was not steeper than 6°. Water content at this site varied between 19% and 67% by fresh weight. The soil had a podzol profile with a sandy loam from a glacial till. About 45% of the trees in the stand were Scots pine (Pinus sylvestris L.) and 55% Norway spruce (Picea abies L. Karst.). The mean stem diameter at the site was 24.3 cm and there were 680 trees per hectare with a mean age of 69 years.

The study site for paper IV was located in Slipstensjö (N 64.469795°, E 19.626619° WGS84) in northern Sweden. The tests were conducted on a flat and firm area consisting of asphalt and gravel roads.

3.3 Equipment, methods, measurements and calculations

3.3.1 Inventories

A sample plot inventory, using the National Forest Inventory (NFI) method (Anon 2009), was carried out in May 2007 for 161 fairly distributed points in the Krycklan catchment area for paper I. The moisture content was measured with Time Domain Reflectometry (TDR) at a depth of 6 cm at three locations adjacent to all of the sampling points. TDR measures the velocity of a pulse of radio frequency energy travelling through a sample. The velocity is dependent on the dielectric constant of the sample, which in turn is dependent on the moisture content (Stafford 1988).

Tests to characterise the bearing capacity of the soil for paper I were carried out at three locations for each sampling point, using a modified Swiss Rammsonde. The mean for these three points was calculated. The Rammsonde used was a cone penetrometer with a hollow aluminium shaft. This shaft has an outside and inside diameter of 20 and 13 mm respectively, a 53° conical tip with a diameter of 40 mm (weight 14.17 N) and a drop hammer with a 12 mm diameter aluminium guide rod (weight 40.45 N). Both the shaft and the rod have centimetre scales. The guide rod is inserted into the hollow shaft. In operation, the hammer with the guide rod is raised by hand to 40 cm and then dropped. The pressure-sinkage after 5, 10 and 15 drops is read from the centimetre scale on the shaft. The Rammsonde pressure is calculated according to (Bodin 1999):

$$p = \frac{\frac{W \cdot h \cdot n}{z} + W + Q}{A}$$

Equation 3

Where:

p	Rammsonde pressure [Pa]
W	Weight of the drop hammer, [N]
h	Height of drop hammer [cm]
n	number of hammer drops
Q	Weight of penetrometer [N]
A	Area of cone base [m^2]

3.3.2 Terrain indices

The Krycklan catchment area was scanned in 2006 using airborne laser scanning (light detection and ranging, LiDAR), with a resolution of approximately one metre (Wallerman, 2007). Landscape analysis was performed using a combination of field observations, a quaternary deposits coverage map (1:100,000, Geological Survey of Sweden, Uppsala, Sweden) and gridded digital elevation models (DEMs) at 0.5 m, 5 m, 10 m, 20 m, 50 m and 100 m grid resolutions. The 0.5 m DEM was constructed from LiDAR measurements with a point density of 3.3 – 10.2 per m^2. Built-in algorithms for terrain analysis in SAGA GIS (Böhner and T. Blaschke 2008) were used to resample the 0.5 m DEM to lower resolutions as well as to remove sinks and to delineate watersheds in the lower resolution DEMs (> 0.5 m).

A total of twelve terrain indices were calculated for paper I. All terrain indices were derived from the 5 m resolution DEM. Only the topographic wetness index (TWI) was additionally calculated for a range of DEMs with different resolutions (5 m, 10 m, 20 m, 50 m, and 100 m). Slope ($\tan(\beta)$), profile curvature (κ_v) and plan curvature (κ_h) were calculated to quantify local surface morphometry (Zevenbergen and Thorne 1987) which can conceptually be related to flow velocity and changes in flow velocity (Moore, Grayson et al. 1991). Single direction flow analysis (O'Callaghan and Mark 1984) was used to calculate horizontal and vertical flow path lengths (λ_h, λ_v) from every point to the nearest downslope surface water body represented by streams, lakes and wetlands. These flow path lengths locate points relative to surface water and are therefore indirect measures of groundwater position and soil humidity. The TWI has a similar significance (Beven and Kirkby 1979) and was calculated based on catchment area and slope calculated by applying the multiple-flow-direction algorithm (Seibert and McGlynn 2007) to DEMs with grid cells of different lengths (x, $x = 5\ m, 10\ m, 20\ m, 50\ m, 100\ m$):

$$TWI_x = \ln\left(\frac{A}{x \cdot \tan(\beta)}\right) \qquad \text{Equation 4}$$

The sensitivity of the TWI to changes in resolution (Sørensen and Seibert 2007) and the challenge of calculating the TWI across areas with different soil parent material (till and sediment) (Grabs, Seibert et al. 2009) were the principal reasons to perform a multi-scale analysis of the TWI. Yearly net shortwave solar radiation (R_n) was used as an indicator of potential evaporation.

3.3.3 Forestry machines

In study II, we used an El-Forest F15, which is the world's first hybrid electric forwarder. It has a type of transmission drive system that is relatively new in Swedish forestry (El-Forest 2010), consisting of three individually steerable axles combined with an electric-hybrid transmission drive system. This system includes an individual speed control for each wheel. As a result of the steering design and the individual speed control of each wheel, the wheels always follow the same tracks. The Valmet 860 is a common forwarder in Swedish forestry and was used as a reference machine in study II. It has the most common transmission drive system found on a conventional forwarder: a hydrostatic transmission drive system consisting of a hydraulic pump and motor where the hydraulic motor is connected, via cardan shafts, to a mechanical transmission in each bogie. All wheels are driven using mechanical transmission.

In study IV, a Vimek 608 forwarder was used as both reference and test machine. Here, the interesting part was the bogie concept. One of the machines was equipped with a conventional bogie and the other with an LTB. The LTB consists of a big driving wheel which is connected to and aligned with the chassis's main axis (Figure 6). A bogie frame is mounted on the wheel axis but left to rotate freely up to a maximum angle. Smaller wheels are mounted on the frame legs with the plane of their axes parallel to the driving wheel. The smaller wheels rotate freely. The three wheels are covered by a single conventional forestry machine metal track.

3.3.4 Rut depth and width measurements

In study II, the rut depth was measured at both study sites. The rut depth was measured using a measuring device consisting of a stand and a movable rod with a centimetre scale. The stand (Figure 4) is placed outside the lump on each side of the track. The rut depth is then measured in the middle of the track using the movable rod. The rut width was measured using a measuring tape with a centimetre scale.

Figure 4. Rut depth measurements for study II.

3.3.5 Simulations

In study III, we used a non-smooth rigid multibody dynamics framework. In this framework, a mechanical system is modelled as a collection of rigid bodies of various geometric shapes and masses. Articulated mechanisms are modelled by imposing kinematic constraints on the relative positions and velocities of these bodies e.g. a hinge constraint for connecting wheel and wheel axes to the chassis. These constraints give rise to additional (constraint) forces applied to the Newton-Euler equations of motion. Secondary constraints can be imposed on the remaining degrees of freedom to model motors, joint limits and internal friction. Impacts and frictional contacts are introduced dynamically as additional constraints obeying the Signorini-Coulomb law, triggered by the contact detection process. Frictional contacts and secondary constraints bring complementarity conditions to the equations of motion and make the velocity discontinuous in time i.e. non-smooth. The simulations were performed using the AgX Multiphysics Toolkit version 1.10 (Simulations, 2011). Gravity was set to 9.81 m/s^2, the time step set to 0.01 s and direct solver settings for both normal and frictional forces.

3.3.6 Acceleration

For paper III, acceleration was calculated whilst for paper IV, the acceleration was measured. For every pass over an obstacle in paper IV, the momentary acceleration and the angular orientation around three axles (roll, pitch, yaw) of the machine were recorded with an Xsens MTi-G accelerometer (Rehn, Lundström et al. 2005).

3.3.7 Slip

In paper IV, we measured the slip between the bogie and the ground. This was achieved by simultaneously measuring the distance the machine travelled as well as the revolutions of the drive axle. Both measurements were made by using shaft encoders sending pulses for each revolution. One encoder was placed on the axis of the drive axle and one was placed on an extra wheel attached to the machine and rolling beside it when driving. Calculating the difference between the theoretical distance travelled by the drive wheel and the actual distance travelled gives the slip.

3.3.8 Towing force

The towing force used in paper IV was measured using a load cell, which measures the force pulling the load cell in two directions. The load cell was placed between the two machines which were connected together with straps. This meant that one machine pulled the other via the load cell.

3.3.9 Statistics

Least squares linear regressions, produced using Minitab (2010), were calculated to predict RP in paper I on the basis of the available parameters. The forestry register data were divided into indicator variables for use in the regressions. The regressions for RP were calculated for all measurements at $p \leq 0.10$. RP was predicted using soil moisture, terrain indices and forestry register data, both as individual parameters and in combination. The regression models were constructed by first creating a regression model with all parameters and then removing the ones that had the highest p-value, one by one. The residuals were examined and the steps were repeated until all remaining parameters had a p-value equal to or less than 0.10. In addition, the data were divided into plots of sedimentary soils and till. The model with the highest adjusted coefficient of determination was used on the whole data set to distinguish areas with soft ground from areas with a higher bearing capacity. An RP of 985 kPa (Eliasson 2005) was selected as the threshold between the two groups. The result was compared with the measured data to determine the number of points that were placed in the correct group.

Analysis of variance, using the GLM procedure in MINITAB(2010), was applied in study II to access effects of different factors on the rut depths and rut widths. It was also used in study IV to test the differences in acceleration and towing force between bogie principles. Prior to running the tests, data were tested for homogeneity of variance (using Levene's statistic). Subsequent multiple comparisons were made using Tukey's tests. Treatment effects were considered significant if $p \leq 0.05$.

4 Result and Discussion

4.1 General results

The most important results from the studies were:

- The Rammsonde pressure generally decreases with increased soil moisture content (paper I)
- There is a difference in the relationship between Rammsonde pressure and soil moisture for till and sediment deposits (paper I).
- The variation of Rammsonde pressure was low (standard deviation of 238) for values up to 700 kPa and the variation increased substantially (standard deviation 526) above that level, indicating the presence of stones and rocks (paper I)
- By combining forestry register data and terrain indices to find the Rammsonde pressure on till soil**,** 73% of the measurements correctly classified low or high bearing capacity ground (paper I).
- The highest value (about 47%) was achieved for till samples when combining terrain indices and register data (paper I).
- On soft arable land, an unloaded forwarder with individually steerable wheels driving straight forward formed deeper ruts than a conventional forwarder with and without bogie tracks, independent of the number of passages. When loaded machines were tested, the conventional forwarder with tracks formed the shallowest ruts. No difference could be established for loaded machines without bogie tracks (paper II).
- A forwarder with individually steerable wheels formed smaller ruts (rut depth) than a conventional forwarder when driving in a straight line on forest land (paper II).
- A forwarder with individually steerable wheels made narrower ruts when turning on both forested land and arable land (paper II).

- The simulations show that the LTB negotiates low obstacles more smoothly than a conventional bogie and it can negotiate wider ditches (paper III). The results were to some extent then confirmed by live tests (paper IV).
- The soil displacement from the LTB is also smaller when turning, as shown by simulations (paper III).
- The mean towing force for the unloaded machine equipped with the LTB on firm ground was 62% higher than the conventional bogie (paper IV).
- The rolling resistance on firm ground for unloaded machines was higher for the conventional bogie compared to the LTB (paper IV).

The results from all the papers combined indicate that it should be possible to reduce ground damage by using predictions of bearing capacity for the actual stand to choose a relevant machine. Further, it seems possible to develop the bogie/transmission and steering systems of the forestry machines to adjust the contact area to match the actual bearing capacity of the ground.

By developing tools for rut planning at a stand level using remote sensing and pre-existing forestry register data, more extensive rut planning can be carried out beforehand without visiting the forest site. This will lower the cost of planning since it is no longer necessary to visit the forest site prior to harvesting. If tools that could classify the bearing capacity of the ground were to be developed, it is more likely that you could plan what kind of machines and equipment you needed to do the job. Machines with low ground pressure can be chosen when driving on soft ground and machines with a low contact area can be chosen to run on firm ground. This will reduce the soil displacement when turning on firm ground. Choosing the correct machine and equipment for a stand would be an easy task if the forest was homogeneous with an equal bearing capacity over the stand. However, the boreal forest is diverse and the bearing capacity can change over small areas. Therefore, machines that are suited to both firm and soft ground are required.

A suggested plan of action for harvesting without causing ground damage is shown in Figure 5.

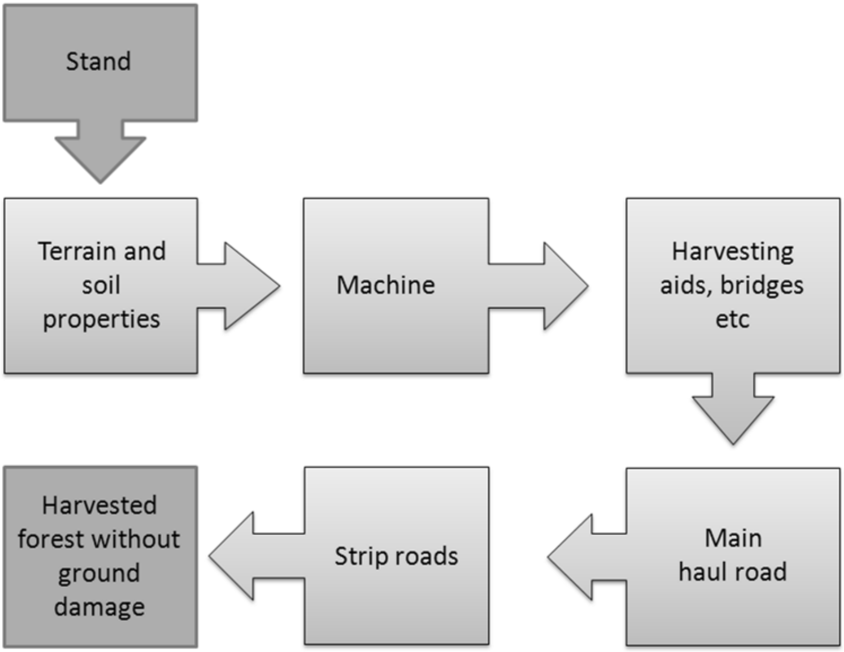

Figure 5. Suggested method of planning a harvest with consideration of ground damage.

Assuming it is a stand to be harvested, the first step is to examine the terrain and soil properties by using the tools developed for paper I and other studies. When you know the type of stand to be harvested and the bearing capacity of the ground, you can choose the machine accordingly. In some cases, there may be small streams or wet areas that need to be crossed; therefore, harvesting aids such as terrain bridges or slash may be required. After that, the main haul road and the strip roads are located so that all trees can be reached and ground damage can be avoided without the need for too many detours. The goal is to harvest the forest without ground damage.

A further explanation of the steps in this plan of action to avoid ground damage is given below.

4.2 Parameters affecting the bearing capacity of the ground

The result from paper I showed that soil moisture did not affect the bearing capacity as much as had been believed earlier (Wronski, Stodart et al. 1989; Staland and Larsson 2002; Liu, Ayers et al. 2010). We also showed that the bearing capacity was dependent on the presence of mobile soil water, the texture of the ground, the soil depth and soil type, the structure of the surface, what kind of flora grew on the field and ground layer, the presence of slopes, ditches and the dominant tree species. It was shown that the regression for bearing capacity (Rammsonde pressure) had a higher coefficient of determination for till deposits than for sediment deposits (Table 2).

Table 2.*The adjusted coefficient of determination in percent ( ) for regressions of the RP and different combinations of soil moisture, terrain indices and forest register data (paper I).*

Data	Soil Moisture	Terrain Indices	Register Data	Soil Moisture + Terrain Indices	Soil Moisture + Register Data	Terrain Indices + Register data	Soil Moisture + Terrain Indices + Register Data
All data	12.5	16.0	19.1	22.3	28.1	34.9	31.1
Till samples	15.0	22.8	27.5	28.2	33.1	46.7	35.7
Sediment samples	10.4	15.9	4.2	18.5	14,2	37.7	37.3

An explanation for this is that the till can usually be found at higher elevations and on steeper areas compared to the sediment. Another important factor is that the till and sediment have different abilities to hold moisture (Whitlow 2001). This factor is especially important during spring, when the soil is wet since the soil moisture can vary a great deal between sediment and till deposits.

In addition, the Rammsonde pressure is dependent on aspects of location and time. The bearing capacity can vary hugely over time and area. In study I, we carried out the measurements during late spring/early summer. The results might be different if the same tests were performed during summer or autumn. Since the boreal forest is so diverse and the presence of roots and stones greatly affects the bearing capacity, the bearing capacity can change rapidly across a distance of a few metres (paper I).

4.3 Classification of bearing capacity to avoid soil damage

When we classified the bearing capacity in study I, we used data that were easily available, either from pre-existing inventories and forestry register data or digital elevation models based on laser scanning. The advantage of using this method is that when applying it to other areas, the data are easy to collect. There are also some disadvantages that cannot be ignored such as parameters that can positively affect the result but are not known. However, we want to classify the forest without having to visit it. One parameter not tested in this study is the stand stem density of the forest and the height of the trees. The taller the trees and the denser the forest is, the more supporting roots lie beneath the topsoil. These roots can increase the bearing capacity considerably (Bygdén and Wästerlund 2007). To be able to use the model developed in study I for classification of bearing capacity, it has to be developed more to achieve a higher accuracy. New parameters could be added and the model needs to be tested on other areas that have not yet been tested.

There are a number of models to characterize the bearing capacity of the ground that already exist. A model to estimate the pressure-sinkage characteristics of the forest floor has been developed by Zeleke et al. (2007). This model is built on a hyperbolic model using Young's modulus; the model can predict the depth of the ruts caused by machinery traffic. The model has one big disadvantage: the Young's modulus must be measured for the soil, therefore the forest site must be visited and the advantage of planning the stand from a computer is thus lost.

There is also a discrete element model developed by Sadek, Chen et al. (2011) that simulates direct shear tests of soil and predicts soil shear behaviour, in terms of shear forces and displacement. The disadvantage with this model is that it is developed for agricultural soil which is more homogeneous than forest soil. No consideration of stone, rock, boulders or roots has been made. Further development is needed to account for the complicated composition on the forest floor with the humus layer and underlying rocks and roots.

4.4 Choosing the correct machine with respect to the bearing capacity of the site

The results from the papers show that there are many parameters affecting the bearing capacity of a forest machine. When choosing which machine to use at a certain site, it is important to consider the total weight of the machine as well as the number of passes that will be made over the same location (Andersson 2010). Most important of all is the bearing capacity of the ground and thus the planning of where ruts will be placed so that weak and wet areas can be avoided.

To choose the correct machine for each forest site with respect to bearing capacity and the risk of ground damage is not an easy task. Even if a correct classification could be achieved without visiting the forest site and the correct machine could be chosen accordingly, it still might not be cost-effective to transport the machine to the forest site. A very specialized machine might have few areas where it can work and it might thus become uneconomical. Therefore, most machines should be adapted to cope with both soft and hard areas. One solution to this problem could be to equip the machines with the LTB, which has an adjustable contact area, or use similar bogie principles.

4.5 Type of bogie and track properties

In studies III and IV, we saw the advantages of having the front and rear bogie wheels lifted off the ground as with the LTB bogie. This created an angle for the bogie track. This angle probably prevented the creation of a bow wave (Figure 1) at the front of the bogie (paper IV). This also greatly reduces the rut width. On the other hand, the ground pressure on firm ground is fairly high compared with a conventional bogie. One opportunity for the future is to further develop the LTB bogie so that the angle of the outer wheels can be manually or automatically adjusted, depending on the bearing capacity of the ground. In other words, when the bearing capacity is low, the rear wheel can be lower to create a bigger area pushing against the underlying ground. If the bearing capacity is very low, even the front wheel can be lowered and when turning, both wheels can be lifted. This also has the advantage that the bogie can be more energy efficient since it requires less energy to drive on one wheel than on two or three when the ground is firm. By the same token, it is more energy efficient to drive on three wheels than on one when the ground is soft.

The result from papers III and IV showed that there was less acceleration using an LTB than a conventional bogie. This result is good from the health perspective of the drivers of the forest machines. Exposure to whole-body vibrations can cause musculoskeletal complications (Rehn, Lundström et al. 2005; Sherwin, Owende et al. 2004).

Additionally, the result from paper III showed that the LTB requires higher torque than a conventional bogie. However, in paper IV the mean towing force to pull the unloaded LTB in neutral gear was lower than for the conventional bogie. These results somewhat contradict the results of the simulation in paper III where it was shown that higher torque was needed for the LTB compared to the conventional bogie. This contradictory result might be explained by the assumptions used in the simulation described in paper III for energy dissipations in the track links for example. Another explanation could be differences in the friction between the tyre and the track. But most importantly, the conventional bogie in paper IV was equipped with a Robson drive, which increases the torque needed to pull the machine. The bogie in the simulation in paper III did not have a Robson drive.

4.6 Steering system

The results from study II showed that a steering system that forces the wheels to follow the same track creates deeper but narrower tracks on soft arable land compared to a conventional steering system (Table 3).

Table 3. *Rut depth as a function of the number of passes for loaded and unloaded machines after driving in a straight line or on an S-shaped or circular course on soft arable land. Means with different letters are different at the 0.05 significance level according to Tukey's multiple comparison tests (paper III). Columns without figures represents situations where critical rut depth already had been reached in the previous passage.*

Propulsion system	Number of passages													
	Without load							With load						
	1	2	3	4	5	8	10	1	2	3	4	5	8	10
Straight														
El-Forest F15	3.4a	4.2a	5.2a	5.8a	6.7a	8.3a	9a	5a	6.2a	7.3a	8.7a	10a	15a	
Valmet 860	3b	3.7b	4.3b	4.8b	5.3b	6.4b	7.3b	4.3b	5.6a	7a	8.4a	9.7a	14.8a	
Valmet 860 tracks	2.1c	3.2c	3.7c	4.1c	4.7c	6.3c	7.2b	1.7b	3.3b	4b	4.6b	5.3b	7.2b	9.3a
Circular														
El-Forest F15	2.4a	2.5a	3b	3.6b	4.5b	5.5b	7b	1.9b	3.6b	5.1c	6.3c	7.5c	11.8b	13.9a
Valmet 860	1.3b	0.4b	1.5c	1.7c	2.1c	5.3b	7.5b	5.2a	6.8a	8.4a	10.1a	12.6a		
Valmet 860 tracks	1.3b	2.8a	4.3a	5.1a	6.5a	9.7a	10.6a	1.6b	3.7b	5.7b	7.7b	9.7b	13.1a	
S-shaped														
El-Forest F15	2.3a	2.6b	3.1ab	3.4b	4.2b	5.8c	6.4b	1.5b	3.3b	4.2b	5b	6.9b	11.1a	
Valmet 860	1.9ab	2.9a	3.4a	4.4a	5.7a	7.5a	8.5a	4.2a	6.5a	8.7a	12a	12.5a		
Valmet 860 tracks	1.4b	2.1b	2.9b	4a	4.1b	6.8b		1.8b	2.8b	4b	5b			

The shearing from the type of steering system where you can control each wheel individually is significantly less than from a conventional bogie. So, there are both pros and cons of a steering system with individually steerable wheels. One advantage is the potential to reduce slipping when turning. This can be done by allowing the outer wheel to travel faster than the inner wheels and, at the same time, allow all the wheels to be turned. On forest land, the ruts became shallower with this kind of steering system compared to a conventional one (Paper II). Since forest machines often drive on forest land, this steering system might have potential especially if it is combined with a bogie principle that allows an adjustable contact area.

4.7 How can ground damage be avoided in the future – is research needed?

To avoid ground damage in the future, it is important to focus both on new techniques and on better planning than is available at present. The ultimate scenario would be that the ground is correctly classified to the extent that the strip roads and tools needed for the harvesting can be planned beforehand using a computer. If that were possible, the cost for each harvest site can be calculated as well as the profit. The forest owner would know if it is profitable to harvest a particular site or not at a certain time.

The forest ground needs to be correctly classified according to bearing capacity, both for the overlying humus and root layer as well as the soil below (Figure 6). Then, the right machine has to be chosen, taking into account the actual bearing capacity, the number of passages over the same rut, if the machine will be driven mostly straight on soft ground etc.

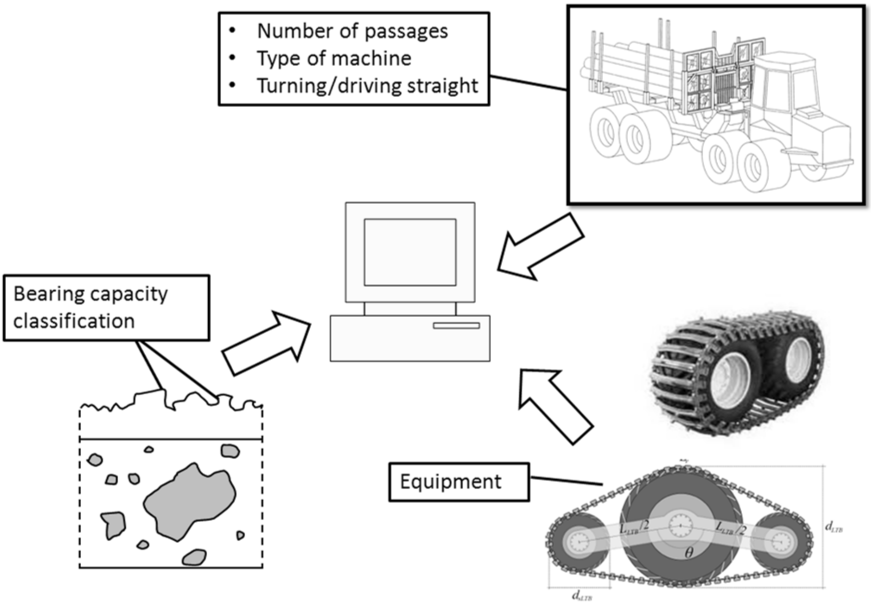

Figure 6. Schematic sketch of how the bearing capacity of the humus layer and the underlying soil layer could be translated into machine parameters such as number of passages and which equipment to use.

The results from papers II, III and IV show that with new technical equipment fitted to the machines, ground damage can be reduced whilst at the same time the accessibility of the machines can be increased. With more research and development on both the steering system and bogie concept, it might be possible to reduce ground damage further. The LTB tested in studies III and IV has the potential to be able to handle soft ground. However, this remains to be tested in field. Another interesting possible development of the LTB is, as discussed, to have an adjustable angle between the big wheel and the small wheels. To lower the rear wheel so that the contact area is increased without losing the advantages of having a raised front wheel could be advantageous not only when driving on soft ground but also when driving in snow. Visual observation during study IV revealed that the bow wave in front of the LTB was much smaller, or did not exist, when driving in snow. The conventional bogie created a bow wave so large that the machine could not be driven at all in the snow conditions experienced during the test.

Figure 7: Illustration showing future possible developments with individually steerable wheels and a bogie concept that allows for adjustable contact area (Ross 2012).

If the results from study II are combined with the results from studies III and IV, we could build a machine equipped with the LTB or other technical principles that give similar mobility but with wheels that were individually steerable (Figure 7). This means that when turning, the other wheel can spin and drive faster; since the other wheel has to travel a longer distance, shearing can be avoided.

Even though we have proved that there is new technical equipment that can be used to reduce ground damage, it is hard to exactly predict the change in bearing capacity for a machine if you change the steering system, for example. To estimate the increased bearing capacity for a special technical solution, more studies need to be carried out. When the ground pressure of the machine is known, you have to match this with a suitable type of ground to drive on. With the RP measurements, you only have the bearing capacity of the ground for a small area. The contact area from the bogie is much bigger than the area measured by the Rammsonde. More research is therefore needed on both describing areas i.e. classifying the ground and new technical equipment for forest machines. The use of computer simulations of the forest floor has the potential for making good estimations of the ground and classifying it according to bearing capacity. One example is the prediction of the pressure-sinkage characteristics of different forest sites developed by Zeleke et al. (2007) that could be further improved.

5 Conclusions

The following general conclusions can be drawn from the studies, conducted in the boreal forest of northern Sweden, underlying this thesis:

1. It might be possible to predict and thus detect soft areas of ground without visiting the forest site even for the critical early summer/spring season (paper I). By more efficient planning of harvesting, strip roads could be located so that wet and soft areas are avoided. Additionally, it should be possible to choose machines in advance with the appropriate ground pressure for a certain area.

   The combination of terrain indices and forestry register data was able to better predict bearing capacity on till in early summer than on sediments. In total, 73% of these points were placed in the correct group. Further development of these models seems appropriate.
2. Machines with a transmission drive system using axles and wheels that can be individually steered seem advantageous, especially for reducing rut formation when turning on both soft and firm ground. When driving in a straight line on soft land, a forest machine with conventional bogie and conventional tracks and steering system gives shallower ruts independent of the number of passages.
3. On intermediate/firm forested land, a machine with a transmission drive system using axles and wheels that can be individually steered forms less ruts than a conventional forest machine equipped with a bogie both when driving in a straight line and when turning. The rut depth increases with the number of passages and with load.
4. The three-wheeled LTB bogie with the front and rear wheel lifted from the ground combine the advantages of both a wheeled machine and a bogie machine. The LTB, using selected design parameters, should produce significantly less soil displacement than the conventional bogie when

turning on firm ground (paper III). A machine equipped with the LTB can negotiate wider ditches than a machine with a conventional bogie. It also has a bigger contact area on soft ground. The smoothness of passing smaller obstacles, measured by acceleration, is similar to that of a conventional bogie (paper IV).

5. The towing force is higher for a bogie with the front and rear wheel lifted from the ground than a conventional bogie equipped with a Robson drive when tested with unloaded machines on firm ground. The rolling resistance on firm ground with unloaded machines is lower for the LTB than a conventional bogie (paper IV).

6 Further development

The combined results from papers I – IV show that it is possible to reduce both the amount and the severity of ground damage by using new bogie principles and better rut planning.

By further development of the new bogie principles with the results from papers II, III and IV, bogies that can be individually steerable and with adjustable ground pressure can be developed. Since the bearing capacity of the forest floor can vary over a wide range, a bogie with adjustable ground pressure would be advantageous. When the ground is firm, the machine can be set to have high ground pressure. The low contact area on the ground will decrease the amount of energy needed to drive the machine forward. Additionally, the soil displacement will also be less when turning.

On ground with low bearing capacity, the ground pressure can be set to be low; this will also decrease the amount of energy needed to drive. With the help of the individually steerable bogies, the soil displacement when turning can be minimized despite the big contact area with the ground.

In conclusion, with further development of new bogie principles and with better rut planning, it is possible to develop smarter and more energy efficient bogie types and, with better rut planning, also reduce the amount of ground damage.

7 References

Alakukku, L. (1996). Persistence of soil compaction due to high axle load traffic. II. Long-term effects on the properties of fine-textured and organic soils. *Soil and Tillage Research* 37(4): 223-238.

Alakukku, L., P. Weisskopf, W.C.T. Chamen, F.G.J. Tijink, J.P. van der Linden, S. Pires, C. Sommer & G. Spooner (2003). Prevention strategies for field traffic-induced subsoil compaction: a review: Part 1. Machine/soil interactions. *Soil and Tillage Research* 73(1-2): 145-160.

Andersson, E. (2010*). Increased harvesting possibilities with suitable ground pressure from the harvesting machines*. Master Thesis. *Institutionen för skoglig resurshushållning*. SLU, Umeå.

Ansorge, D. and R. J. Godwin (2007). The effect of tyres and a rubber track at high axle loads on soil compaction, Part 1: Single axle-studies. *Biosystems Engineering* 98(1): 115-126.

Ayers, P. D. (1994). Environmental damage from tracked vehicle operation. *Journal of Terramechanics* 31(3): 173-183.

Berg, S. (1992). Terrain classification for forestry work. Uppsala, Sweden, Skogforsk.

Berg, S. (2011). Vad är en körskada? *Skogforsk Resultat 3.*

Berggren, M., L. Ström, H. Laudon, J. Karlsson, A. Jonsson, R. Giesler, A.-K. Bergström, M. Jansson (2010). Lake secondary production fueled by rapid transfer of low molecular weight organic carbon from terrestrial sources to aquatic consumers. *Ecology Letters* 13: 870-880.

Beven, K. J. and M. J. Kirkby (1979). A physically based, variable, contributing area model of basin hydrology *Hydrological Sciences* 24(1): 43-69.

Björkvald, L., I. Buffam, H. Laudon & C.M. Mörth (2008). Hydrogeochemistry of Fe and Mn in small boreal catchments: The role of seasonality, landscape type and scale. *Geochimica et Cosmochimica Acta*(72): 2789-2804.

Bodin, A. (1999). Development of a tracked vehicle to study the influence of vehicle parameters on tractive performance in soft terrain. *Journal of Terramechanics* 36: 167-181.

Bygdén, G., Eliasson, L. & Wästerlund, I. (2003). Rut depth, soil compaction and rolling resistance when using bogie tracks. *Journal of Terramechanics* 40(3): 179-190.

Bygdén, G. and Wästerlund I. (2007). Rutting and soil disturbance minimized by planning and using bogie tracks. *Forestry studies* 46: 5-12.

Böhner, J. and Blaschke E.A.T (2008). SAGA: System for an automated geographical analysis. *Hamburger Beiträge zur Physischen Geographie und Landschaftsökologie. Hamburg, Institute of Geography, University of Hamburg*.

Chamen, T., L. Alakukku, S. Piresc, C. Sommerd, G. Spoore, F. Tijinkf & P. Weisskopfg. (2003). Prevention strategies for field traffic-induced subsoil compaction: a review. Part 2. Equipment and field practices. . *Soil and Tillage Research* 73(1-2): 161-174.

Edlund, J., B. Löfgren, & U. Bergsten (2012). Effects of two different forwarder steering and transmission drive systems on rut dimensions. *Journal of Terramechanics, In Press.*

El-Forest. (2010). *Energy efficient and environmentally sound forestry machinery of the future*. www.el-forest.se [2012-09-21]

Eliasson, L. (2005). Effects of forwarder tyre pressure on rut formation and soil compaction. *Silva Fennica* 39(4): 549-557.

Eliasson, L. and Wästerlund I. (2007). Effects of slash reinforcement of strip roads on rutting and soil compaction on a moist fine-grained soil. *Forest Ecology and Management* 252(1-3): 118-123.

Enström, J. (1996). *Grundbok för skogsbrukare*. Jönköping, Skogsstyrelsen.

European Parliament, C. (2000). *The EU Water Framework Directive, The European union's publication bureau*.

Fullen, M. A. (1985). Compaction, hydrological processes and erosion on loamy sands in east Shropshire, England. *Soil Till. Res*. 6: 17-29.

Gideon, G. (1992). Bearing Capacity of Soils. *Engineering Manual No. 1110-1-1905. U. S. A. C. o. Engineers. Washington.*

Grabs, T., Seibert J., Bishop, K. & Laudon H. (2009). Modeling spatial patterns of saturated areas: A comparison of the topographic wetness index and a dynamic distributed model. *Journal of Hydrology* 373(1-2): 15-23.

Greacen, E. L. and Sands R. (1980). Compaction of forest soils. A review. *Aust. J. Soil Res.* 18: 163-189.

Hallonborg, U. (1982). *Ristäckets inverkan på spårbildningen*. Forskningsstiftelsen Skogsarbeten nr 3, 1982

Hirota, T., Iwata, Y., Hayashi M. & Suzuki S. (2006). Decreasing soil-frost depth and its relation to climate change in Tokachi, Hokkaido, Japan. *Journal of the Meteorological Society of Japan* 84(4): 821-833.

Hummel, J.W., Ahmad, I.S., Newman, S.C., Sudduth, K.A. & Drummond, S.T. (2004). Simultaneous soil moisture and cone index measurement. *American Society of Agricultural Engineers* 47(3): 607-618.

Jäghagen, K. and J. Sandström (1994). *Alla Tiders Skog.* Skogsägarnas Riksförbund, Trelleborg

Knutsson, M. (2001). *Tjäldjupsberäkningar med temperatursummor*. Master Thesis. Institutionen för geovetenskap. Uppsala Universitet, Uppsala

Kärhä, K. and A. Poikela (2010). Harvesting wood from spruce swamp stand during summer. *Oscar conference*, Honne, Norway.

Laudon, H., M. Berggren, A. Ågren, I. Buffram, K. Bishop, T. Grabs, M. Jansson & S. Köhler (2011). Patterns and dynamics of dissolved organic carbon (DOC) in boreal streams: the role of processes, connectivity, and scaling. *Ecosystems, published online 28 May 2011*.

Liu, K., P. Ayers, H Howard & A Anderson. (2010). Influence of soil and vehicle parameters on soil rut formation. *Journal of Terramechanics* 47: 143-150.

Magnusson, T. (2009). *Skogsskötselserien nr 13. Skogsbruk, mark och vatten,* Skogsstyrelsen.

McDonald, P. T. & F. Seixas (1997). Effect of Slash on Forwarder Soil Compaction. J. *For. Eng.* 8(2): 15-26.

Mellander, P.-E., M.O. Löfvenius, H. Laudon, et al. (2007). Climate change impact on snow and soil temperature in boreal Scots pine stands. *Climatic Change* 85: 179-193.

Minitab® Statistical Software 2010, State College PA

Moore, I. D., R. B. Grayson, A.R. Ladson. (1991). Digital terrain modelling: a review of hydrological, geomorphological and biological applications. *Hydrological processes* 5: 3-30.

Myhrman, D. (1990). Factors influencing rut formation from forestry machines. *10th International conference of the ISTVS, Kobe, Japan*.

O'Callaghan, J. F. & D. M. Mark (1984). The extraction of drainage networks from digital elevation data. *Computer vision, graphics, and image processing* 28(3): 323-344.

Poikela, A. (2011). Harvesting wood from spruce swamp stand during summer. *Oscar Seminar Soil and machine workshop. November 22-23 Hyytiälä, Finland.*

Poršinsky, T., Pentek T., Andreja Bosner & Igor Stankić (2012). Ecoefficient Timber Forwarding on Lowland Soft Soils, Global Perspectives on Sustainable Forest Management, Okia Clement Akais (Ed.), ISBN: 978-953-51-0569-5, InTech, Available from: http://www.intechopen.com/books/global-perspectives-on-sustainable-forest-management/ecoefficient-timber-forwarding-on-lowland-soft-soils

Rehn, B., R. Lundström, L. Nilsson, I. Liljelind & B. Järvholm. (2005). Variation in exposure to whole-body vibration for operators of forwarder vehicles - aspects on measurement strategies and prevention. *Industrial Ergonomics* 35: 831-842.

Rohani, B. and G. Y. Baladi (1981). *Correlation of mobility cone index with fundamental engineering properties of soil*. Washington D.C., Office, Chief of Engineers U.S. Army.

Ross, N. (2012) *Axolotl.* Master Thesis Umeå Institute of Design, Umeå

Sadek, M. A., Y. Chen & J. Liu (2011). Simulating shear behavior of a sandy soil under different soil conditions. *Journal of Terramechanics* 48: 451-458.

Seibert, J. and B. L. McGlynn (2007). A new triangular multiple flow direction algorithm for computing upslope areas from gridded digital elevation models. *Water Resources Research* 43(4).

Sharratt, B., G Benoit, J Daniel & J Staricka. (1999). Snow cover, frost depth, and soil water across a prairie pothole landscape. *Soil Sci.* 164: 483-492.

Sherwin, L. M., PMO Owende, CL Kanali & J Lyons. (2004). Influence of tyre inflation pressure on whole-body vibrations transmitted to the operator in a cut-to-length timber harvester. *Applied Ergonomics* 35: 253-261.

SLU (2009).Fältinstruktion Riksinventeringen av skog. SLU, Umeå

SLU (2010-06-21). *Vindeln and Ätnarova Experimental Forests with Svartberget Research Station*. http://www.slu.se/en/faculties/s/about-the-faculty/departments/unit-for-field-based-forest-research/experimental-forests/welcome-to-vindeln-experimental-forests/ [2012-09-21]

SMHI (2008-09-24) *Sveriges klimat i framtiden* http://www.smhi.se/klimatdata/klimatscenarier/klimatanalyser/Sveriges-lans-framtida-klimat-1.8256 [2012-09-21]

Stafford, J. V. (1988). Remote, Non-contact and in-situ Measurement of Soil Moisture Content: a Review *Journal of agricultural Engineering Research* (41): 151-172.

Staland, F. and K. Larsson (2002). Bra planering och rätt teknik minskar risken för markskador. *Skogforsk Resultat* (4): 4.

Suvinen, A. and M. Saarilahti (2006). Measuring the mobility parameters of forwarders using GPS and CAN bus techniques. *Journal of Terramechanics* 43: 237-252.

Sørensen, R. and J. Seibert (2007). Effects of DEM resolution on the calculation of topographical indices: TWI and its components. *Journal of Hydrology* 347(1-2): 79-89.

Timbear AB. (2012-08-17). *Timbear*. http://www.timbear.se/ [2012-09-21]

Tjerngren, I. (2012). *Redefining the role of wetlands as methyl mercury sources*. Doctoral thesis Acta universitatis agriculturae Sueciae, Institutionen för skogens ekologi och skötsel. Umeå, SLU,Umeå

TrelleborgTwinForestry (2004). Trelleborg, Trelleborg Industri AB.

Törnqvist, J. (2011). Soil pressure calculator. OSCAR Seminar *Soil and machine workshop. November 22-23, Hyytiälä, Finland*

Uusitalo, J., J. Ala-ilomäki, M. Salomäki & P. Niemistö (2011). New solutions in management and harvesting of peatland forests. OSCAR Seminar *Soil and machine workshop. November 22-23, Hyytiälä, Finland.*

Whitlow, R. (2001). *Basic Soil Mechanics*.4th edition, Harlow, Pearson Educational Limited

Wronski, E., D. Stodart, & N. (1989). Trafficability assessment as an aid to planning logging operations. *Appita* 43(1). humphreys

Wronski, E. B. and G. Murphy (1994). Responses of forest crops to soil compaction. *Soil compaction in crop production*: 317-342.

Wästerlund, I. (1989). Strength components in the forest floor restricting maximum tolerable machine forces. *Journal of Terramechanics* 26(2): 177-172.

Wästerlund, I. (1992). Extent and causes of site damage due to forestry traffic. *Scandinavian Journal of Forest Research* 7(1): 135-142.

Zeleke, G., P.M.O. Owende, C.L. Kanali, & S.M. Ward (2007). Predicting the pressure-sinkage characteristics of two forest sites in Ireland using in situ soil mechanical properties. *Biosystems engineering* 97: 267-281.

Zevenbergen, L. W. & C. R. Thorne (1987). Quantitative analysis of land surface topography. *Earth Surface Processes and Landforms* 12(1): 47-56.

Ziesak, M. (2003). *Avoiding soil damages, caused by forest machines*. Dipl. -Forstwirt, Lehrstuhl für Forstliche Arbeitswissenschaft und Angewandte Informatik. München**:** 9.

Ågren, A., I Buffam, M Jansson & H Laudon (2007). Importance of seasonality and small streams for the landscape regulation of dissolved organic carbon export. *Journal of Geophysical Research* 112.