ARBETSRAPPORT 1033-2020

The 294 Rotflakamyran and 296 Trågalidsberget sites

A FIELD STUDY INTO THE ENVIRONMENTAL IMPACT OF FORWARDER TRAFFIC

Fältförsöken 294 Rotflakamyran och 296 Trågalidsberget – en fältstudie om miljöeffekter av körning med skotare

The forwarder stops at the stop line downhill in a study plot where logging mats were used for ground protection. Photo Eva Ring

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Sammanfattning

Spårbildning och markkompaktering orsakat av körning på skogsmark i samband med skogsbruksåtgärder kan påverka skog, mark och vatten negativt. För att öka kunskapen om hur man kan minska markskadorna vid körning på skogsmark startades två fältförsök i norra Sverige år 2012, 294 Rotflakamyran och 296 Trågalidsberget. Syftet med försöken var att undersöka miljöeffekter på kort och lång sikt av att köra med en lastad skotare med och utan markskydd på provytor utlagda utmed fyra avverkade moränsluttningar. De fyra körbehandlingarna som studerades var 1) ingen körning, 2) körning utan markskydd, 3) körning på risbädd och 4) körning på stockmattor. I denna rapport beskrivs de två fältförsöken utförligt som bakgrund till pågående och kommande studier.

Summary

Rutting and soil compaction caused by off-road forestry transportation can adversely affect the forest, soil, and water. A research project, funded by Formas (Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning), was initiated and involved the establishment of two field sites, 294 Rotflakamyran and 296 Trågalidsberget. In 2012 and 2013, studies were conducted in which a laden forwarder was driven over the study plots when the plots had (i) no ground protection, and (ii) ground protection in the form of logging residue or logging mats. The overall project objective was to contribute information that can be used to prevent or mitigate soil damage caused during off-road forestry transportation. The study sites were designed for both short-term and long-term investigations. In this report, the 294 Rotflakamyran and 296 Trågalidsberget sites are described in detail as a background for ongoing and future investigations at the sites.

This is an updated version of the report, published on 4 February, 2021.
Texts and figures have been edited on p. 7 “Site description” line 9,
p. 29 “Rut depth” line 3 and Figs. 6-7.

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Preface

The two field sites described in this report are run by Skogforsk with kind permission of Holmen AB who are hosting the sites on their land. We are grateful for the financial support provided by Formas (Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning) to establish the sites as part of the project “A multi-disciplinary approach to reduce soil disturbance related to forwarder traffic at final felling” (project 2010-1168). Financial support has also been provided by the research programmes ForWater, funded by Formas (project 2010-0089), and Future Forests, supported by the Foundation for Strategic Environmental Research, the Swedish forestry, the Swedish University of Agricultural Sciences, Umeå University and Skogforsk. Funding was received from the research programme EFFORTE (Efficient forestry by precision planning and management for sustainable environment and cost-competitive bio-based industry) with funding from the Bio Based Industries Joint Undertaking under the European Union’s Horizon 2020 research and innovation programme under grant agreement No 720712, and finally from the Swedish Energy Agency (project 41997-1), Svea Jansson Forest Foundation, Norrskog Research Foundation and the Brattås Foundation. Most of the studies carried out at the field sites were collaborations between Skogforsk and the Swedish University of Agricultural Science (SLU). We would like to thank our colleagues at Skogforsk and SLU for valuable field work, especially Sten Nordlund, and Ulf Carlsson and Tomas Lundqvist for the work related to the application of ground protection and driving the forwarder.

Uppsala, December 2019

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Contents

Introduction

In Sweden, an initiative to reduce the environmental impact of off-road forestry transportation was taken by the forestry about a decade ago and resulted in a policy statement (described by Berg *et al*., 2010; Keskitalo *et al*., 2016). Later, the Swedish Forest Act was supplemented with a requirement stating that serious damage as a result of forestry transportation must be prevented, and a strategic objective for off-road forestry transportation has recently been developed in a dialogue process within the Swedish forestry sector (Andersson *et al*., 2016). On-site practices have been developed within operational forestry and research projects have been initiated to investigate best practice for off-road forestry transportation. One research project involved the establishment of two field sites, 294 Rotflakamyran and 296 Trågalidsberget, with the overall objective to contribute information that can be used to prevent or mitigate soil damage caused during off-road forestry transportation. At the Rotflakamyran and Trågalidsberget sites, different aspects of driving a laden forwarder without or with logging residue or logging mats as ground protection have been investigated. In this report, the field sites and their experimental setup are presented in detail.

So far, three studies have been published from the 294 Rotflakamyran and 296 Trågalidsberget sites. Ågren *et al*. (2015) highlighted the potential of depth-to-water (DTW) maps for forestry planning. However, they found, based on the rutting at Rotflakamyran and Trågalidsberget and DTW maps for the sites, that DTW maps cannot be used for predicting rutting. Nevertheless, Ågren *et al*. (2015) concluded that DTW maps can be used to identify areas where rutting can lead to harmful sediment transports in adjacent streams. Hansson *et al*. (2018) studied the physical properties of the upper mineral soil at the study sites using both X-ray and laboratory analysis. They found that the hydraulic conductivity was 70% lower in the wheel tracks than in the soil beside the tracks. The X-ray image analysis indicated that this was due to the smaller total pore volume and lower connectivity of structural pores ($\varphi > 60$ µm). The total porosity was 24% and 12% lower in the tracks at Rotflakamyran and Trågalidsberget, respectively. Simulations with a one-dimensional hydrological model (Hydrus-1D) indicated that the changes in the hydraulic properties of the soil influenced the soil water content in the wheel tracks, mostly during dry periods (Hansson *et al*., 2019). Furthermore, the species composition of the vegetation in the wheel tracks (Ellenberg indicator for soil moisture) corroborated the higher soil water contents measured in the wheel tracks.

View from the Rotflakamyran site. The logging residue and logging mats used for ground protection on the study plots were stored along the forest road prior to application. Photo Eva Ring

The forwarder driving uphill at the Trågalidsberget site on a study plot with logging residue for ground protection. Photo Eva Ring

Aim

The aim of the study was to investigate the short-term and long-term environmental impact of forwarder traffic along harvested till hillslopes using logging residue or logging mats for ground protection. The treatments included: 1) no driving, 2) driving without ground protection, 3) driving on logging residue and 4) driving on logging mats.

Site description

The field sites, 294 Rotflakamyran and 296 Trågalidsberget (hereafter referred to by name), are located 35 km apart in northern Sweden, in the county of Västerbotten (Figs. 1-3). Rotflakamyran (64°32.5' N, 20°4.5' E) is situated at an altitude between 298 and 309 m amsl and Trågalidsberget (64°19.3' N, 20°35.7' E) at an altitude between 140 and 147 m amsl (Figs. 4-7). In this region, the annual mean air temperature is 1-2°C and mean precipitation 600-700 mm yr^{-1} (SMHI, 2019ab).

Both sites contain two hillslopes, with a ditch at the bottom (Figs. 2-3). Rotflakamyran hillslope A has a straight shape while the profiles for the remaining hillslopes are slightly convex (Figs. 4-7). The mean slope inclination of the study plots varied from 4 to 8%. The soil type is orthic (haplic) podzol according to the FAO soil classification system (Hansson *et al.*, 2018).

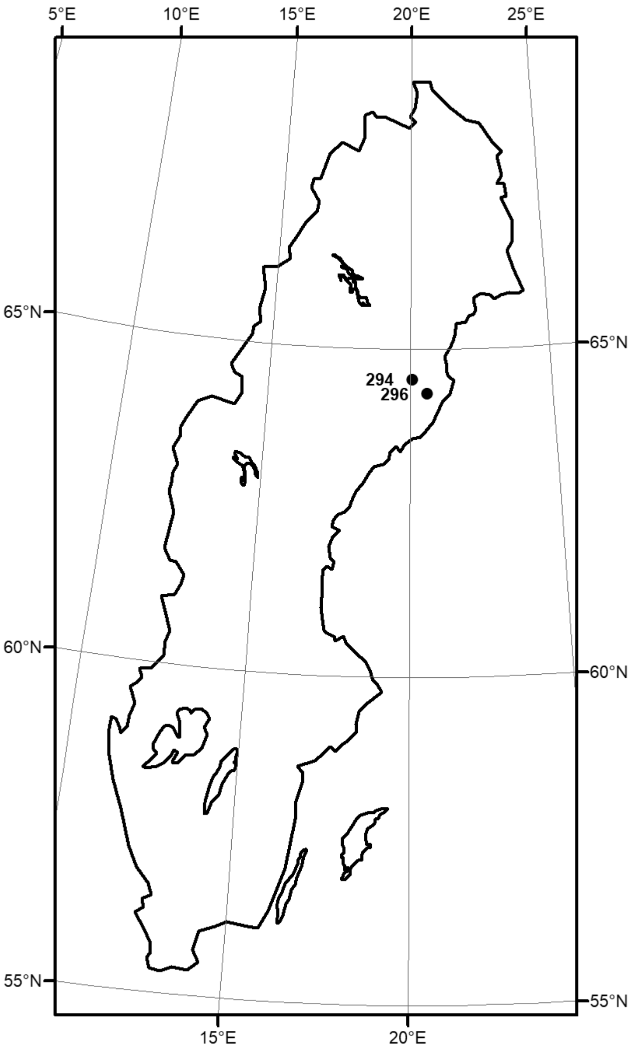


Fig. 1. Map of Sweden with the locations of the 294 Rotflakamyran and 296 Trågalidsberget sites.

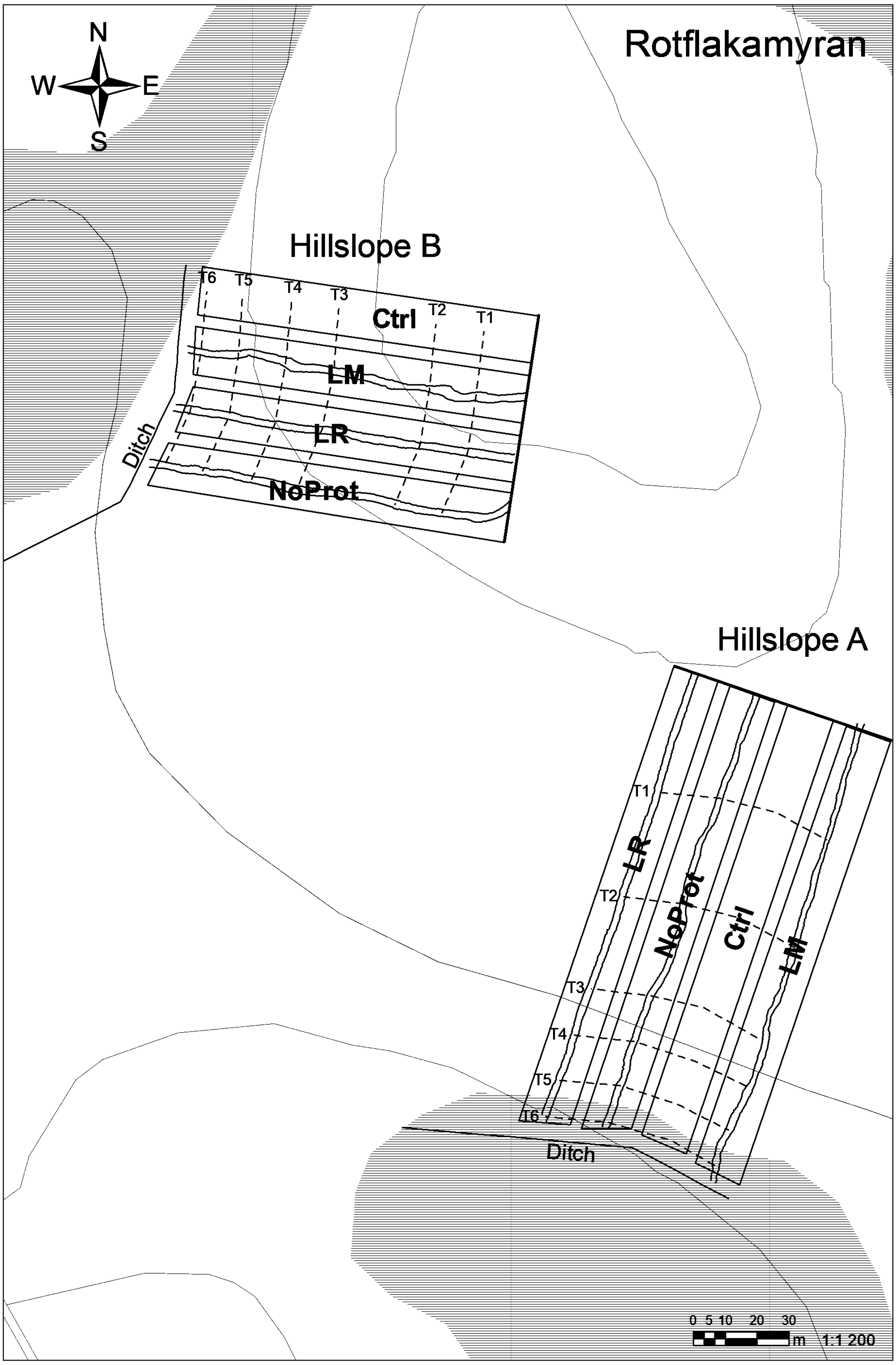


Fig. 2. Map of 294 Rotflakamyran showing hillslopes A and B with four study plots including one untreated control plot ("Ctrl"). The other study plots were subjected to traffic by a laden forwarder using no ground protection ("NoProt"), logging residue ("LR") or logging mats ("LM") as ground protection. T1-T6 show transects 1-6 used for soil sampling. The wheel tracks of the forwarder on the study plots are shown as solid lines. The ditches were located downhill from the study plots. A common start line was defined uphill for each block (thick solid line).

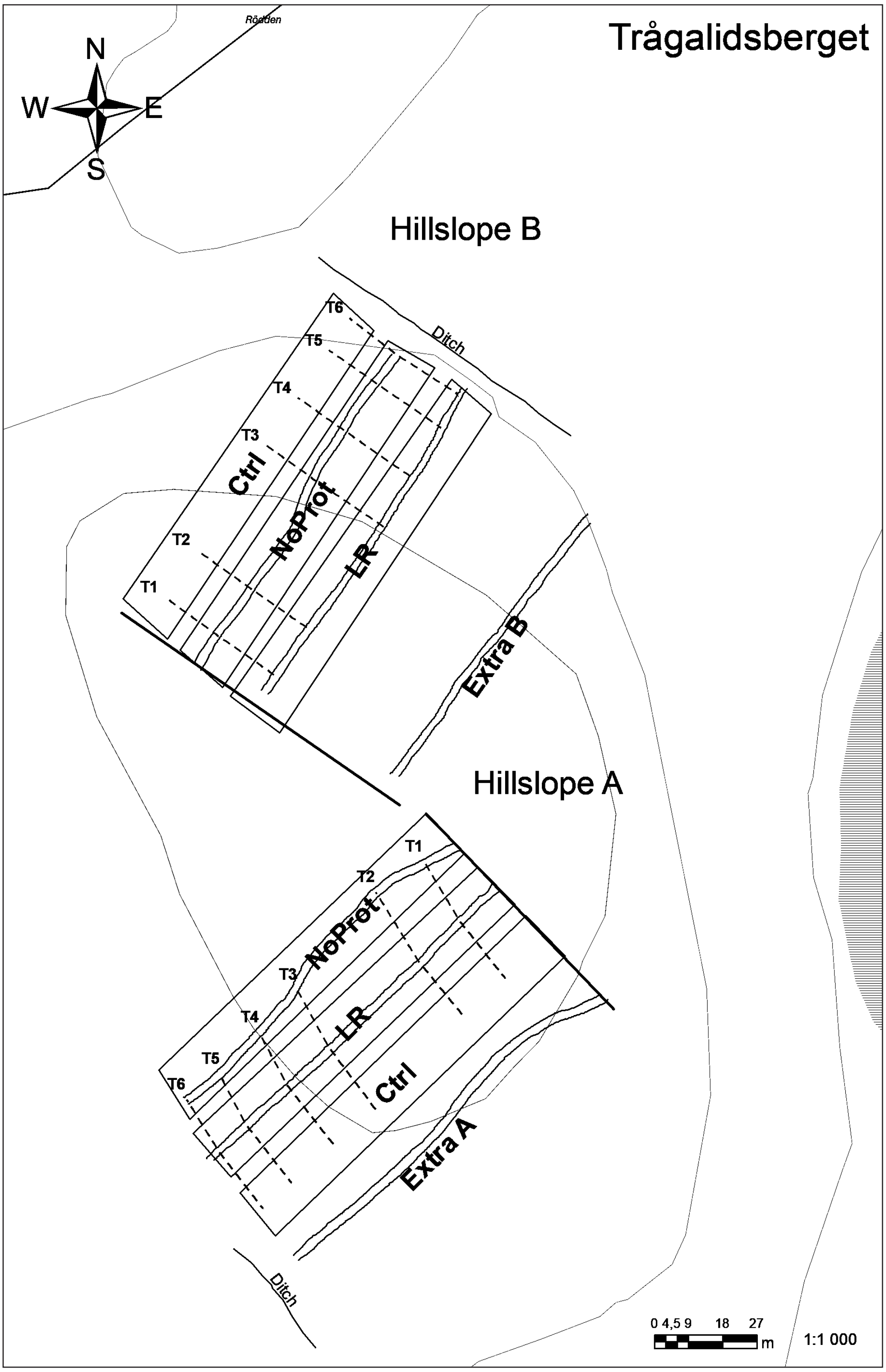


Fig. 3. Map of 296 Trågalidsberget showing hillslopes A and B with three study plots including one untreated control plot ("Ctrl"). The other study plots were subjected to traffic by a laden forwarder using no ground protection ("NoProt") or logging residue ("LR") as ground protection. One extra plot ("Extra") with no ground protection was established on each hillslope. T1-T6 show transects 1-6 used for soil sampling. The wheel tracks of the forwarder on the study plots are shown as solid lines. The ditches were located downhill from the study plots. A common start line was defined uphill for each block (thick solid line).

Rotflakamyran hillslope A

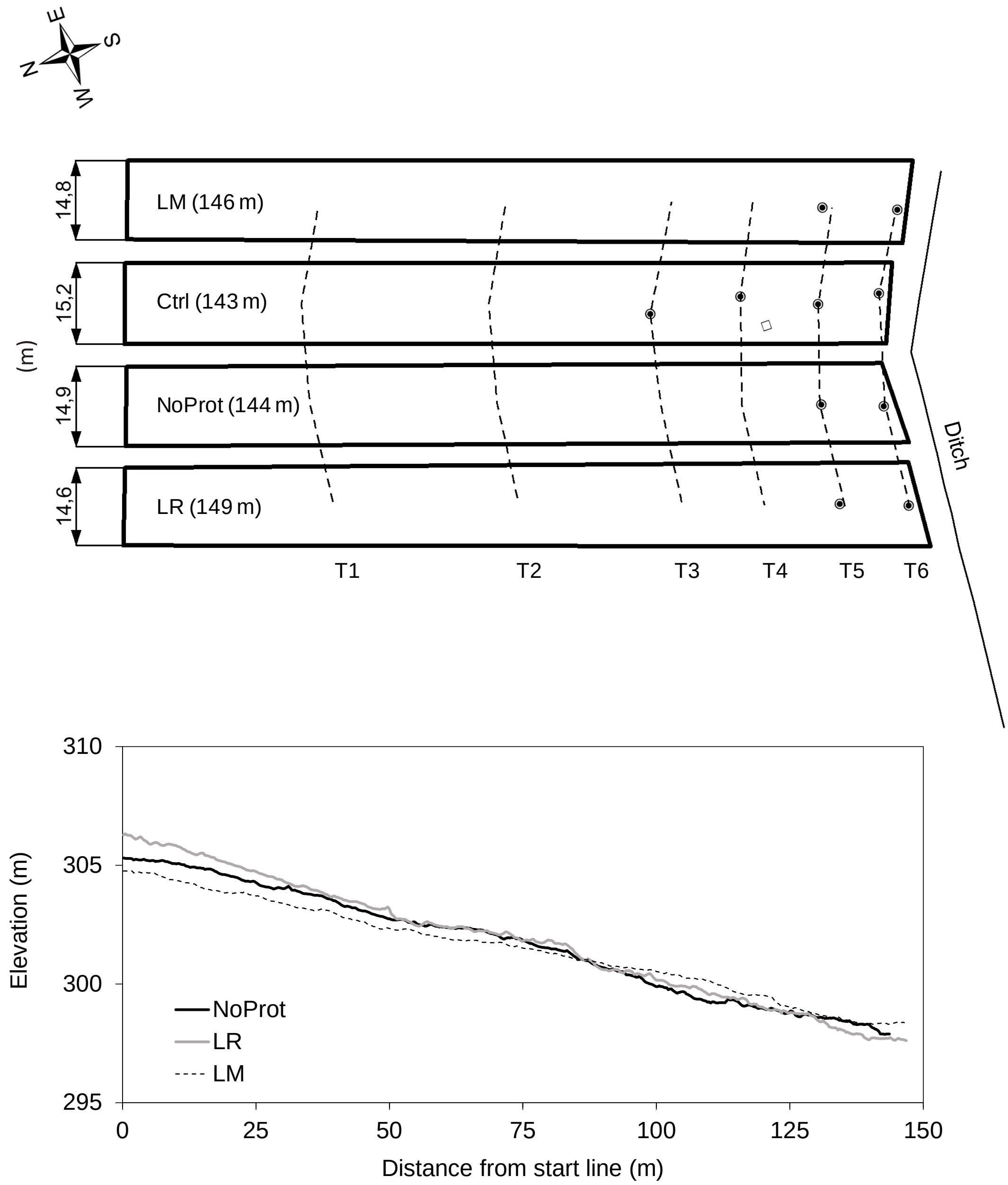
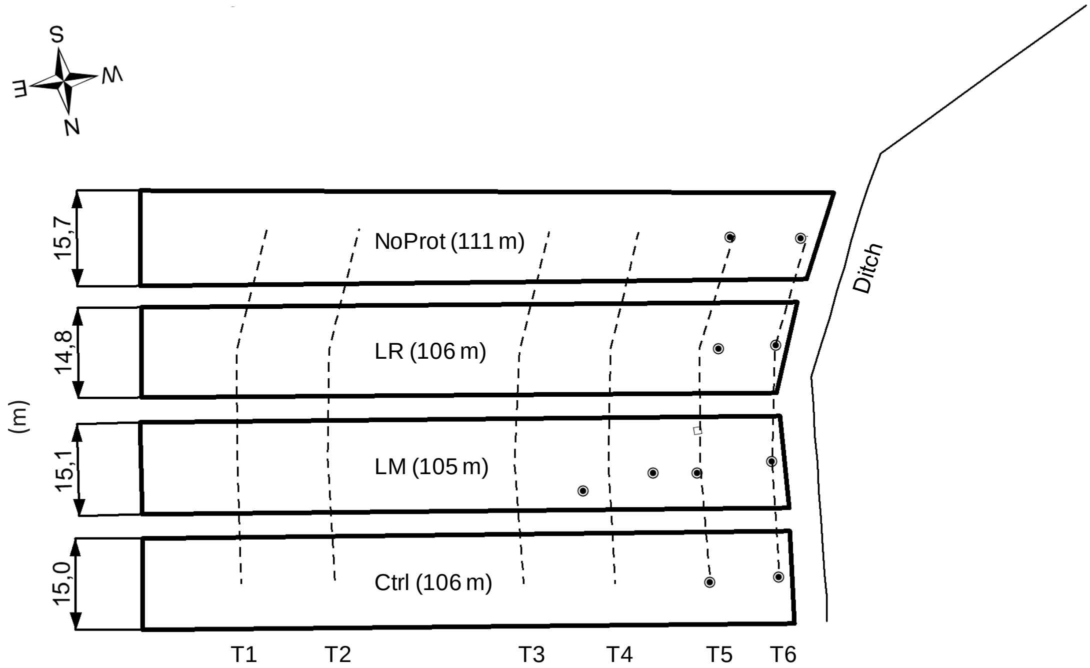


Fig. 4. Top: Size (in metres) of the study plots, and location of groundwater tubes (●), logger (□) and transects T1-T6 at Rotflakamyran hillslope A. Bottom: Hillslope profiles of the study plots subjected to driving (note the different scales on the x- and y-axes, exaggerating inclination). The profiles show the interpolated original soil surface above the right rut, using GNSS-positioning and Triangular Irregular Networks. NoProt: No ground protection, LR: Logging residue, LM: Logging mats.

Rotflakamyran hillslope B



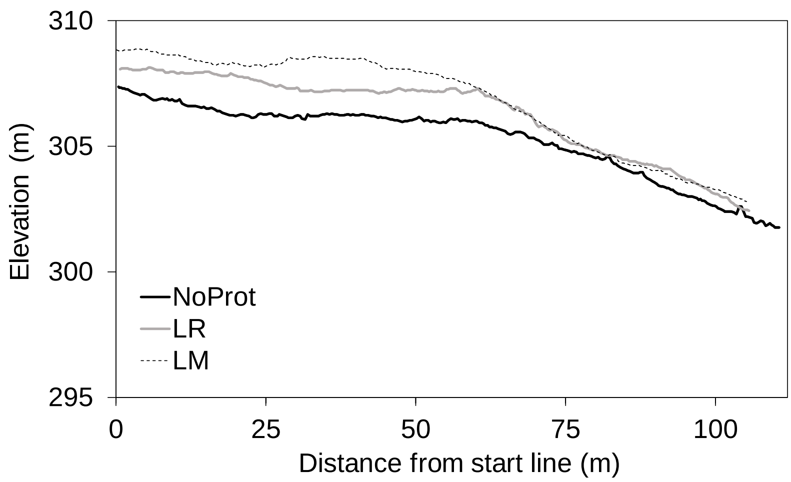
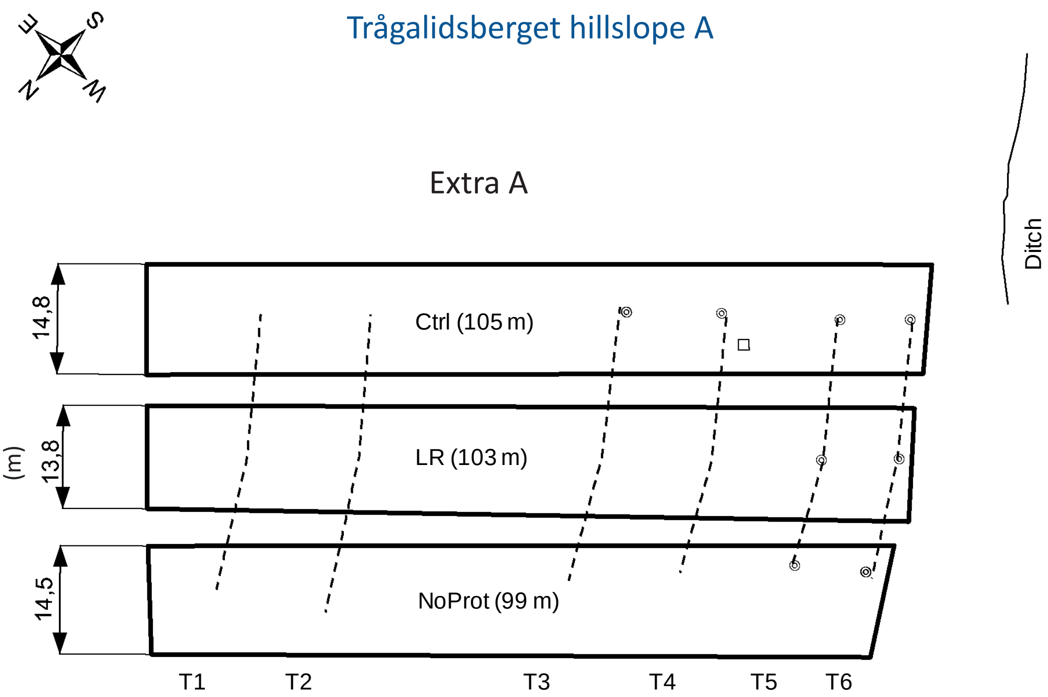


Fig. 5. Top: Size (in metres) of the study plots, and location of groundwater tubes (●), logger (□) and transects T1-T6 at Rotflakamyran hillslope B. Bottom: Hillslope profiles of the study plots subjected to driving (note the different scales on the x- and y-axes, exaggerating inclination). The profiles show the interpolated original soil surface above the right rut, using GNSS-positioning and Triangular Irregular Networks. NoProt: No ground protection, LR: Logging residue, LM: Logging mats.



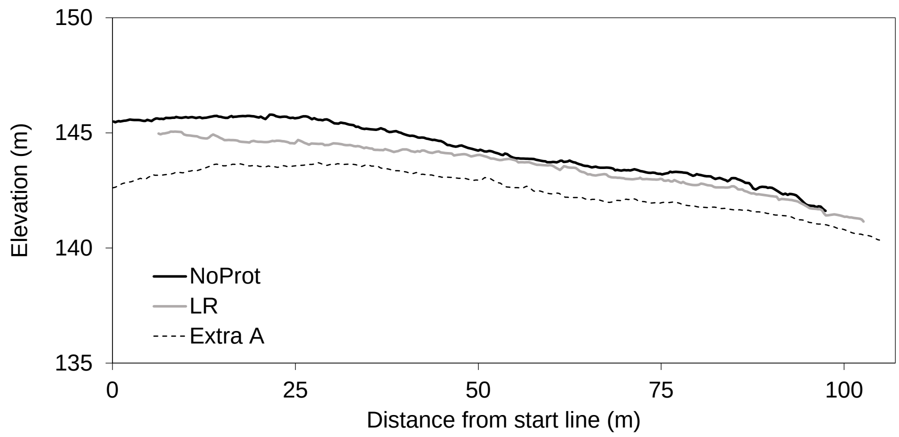


Fig. 6. Top: Size (in metres) of the study plots, and location of groundwater tubes (○), logger (□) and transects T1-T6 at Trågalidsberget hillslope A. Bottom: Hillslope profiles of the study plots subjected to driving (note the different scales on the x- and y-axes, exaggerating inclination). The profiles show the interpolated original soil surface above the right rut, using GNSS-positioning and Triangular Irregular Networks. NoProt: No ground protection, LR: Logging residue, Extra A: Extra plot A.

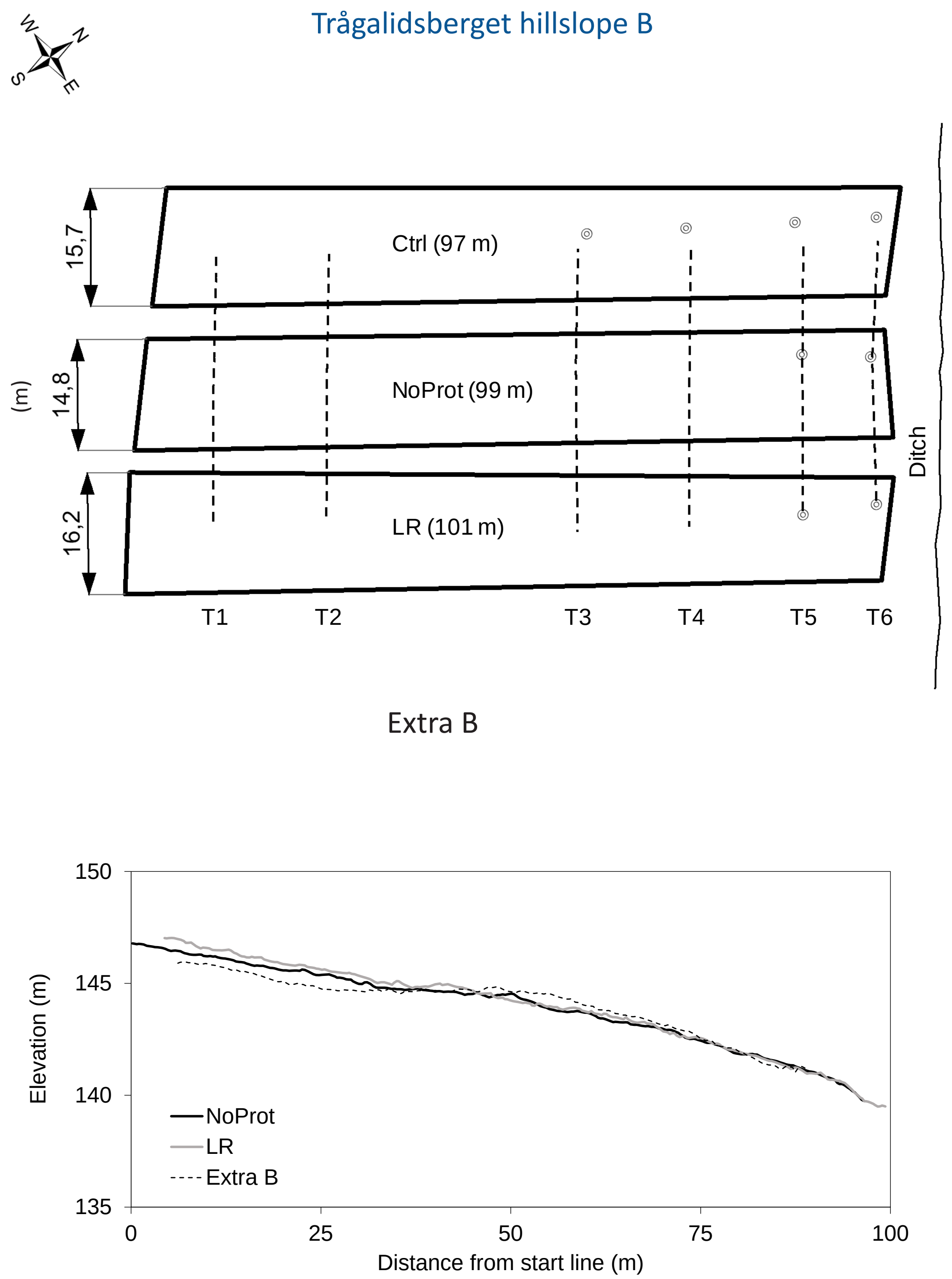


Fig. 7. Top: Size (in metres) of the study plots, and location of groundwater tubes (○) and transects T1-T6 at Trågalidsberget hillslope B. Bottom: Hillslope profiles of the study plots subjected to driving (note the different scales on the x- and y-axes, exaggerating inclination). The profiles show the interpolated original soil surface above the right rut, using GNSS-positioning and Triangular Irregular Networks. NoProt: No ground protection, LR: Logging residue, Extra B: Extra plot B.

THE HARVESTED STANDS

The driving treatments were carried out after logging at Rotflakamyran and Trågalidsberget. Before the logging, the Rotflakamyran site was covered by mixed stands of mainly *Pinus sylvestris* L. and *Picea abies* (L.) H. Karst. On hillslope A, the tree species composition was 40% *P. sylvestris*, 54% *P. abies* and 6% *Betula spp*. (based on the number of stems). On hillslope B, the composition was 47% *P. sylvestris*, 52% *P. abies* and 1% *Betula* spp. Before the logging at Trågalidsberget, the main tree species was *P. abies* (Fig. 8). The tree species composition was 2-3% *P. sylvestris*, 93-94% *P. abies* and 4% *Betula* spp. for both hillslopes. Generally, stem density tended to be higher and mean stump diameter lower at Trågalidsberget than at Rotflakamyran. Stem density and mean stump diameter displayed some variation along the hillslopes (Figs. 9-10).

Apart from describing the study plots, the main purpose of the stump inventory was to assess possible variability in the bearing capacity of the root mat along the study plots. The stumps on the study plots were inventoried with respect to tree species and diameter. The stump inventory, and an assessment of the soil bearing capacity (see Soil penetration depth), were carried out on subplots sized 15 m × 15 m established side by side along the entire hillslope. The stump inventory data represent not only the study plots, but sometimes also adjacent areas uphill and downhill of the short sides of the study plot. The data presented in Figs. 9-10 give an overall picture of the conditions on the studied hillslopes, but caution must be taken if compared with other data since the starting points used may have differed. The stump inventory was undertaken in June 2012, and included all study plots except the control plot on hillslope A at Rotflakamyran (because of lack of time) and the Extra plots at Trågalidsberget. In 2019, the location of the stumps on the plots with no ground protection (NoProt) was assessed using GNSS-positioning (Global Navigation Satellite Systems) with a handheld GNSS-receiver, model Topcon GRS-1 (http://www.topconpositioning.com/) (Figs. 11-12).

Fig. 8. The Norway spruce stand at Trågalidsberget in 2011. Photo Eva Ring

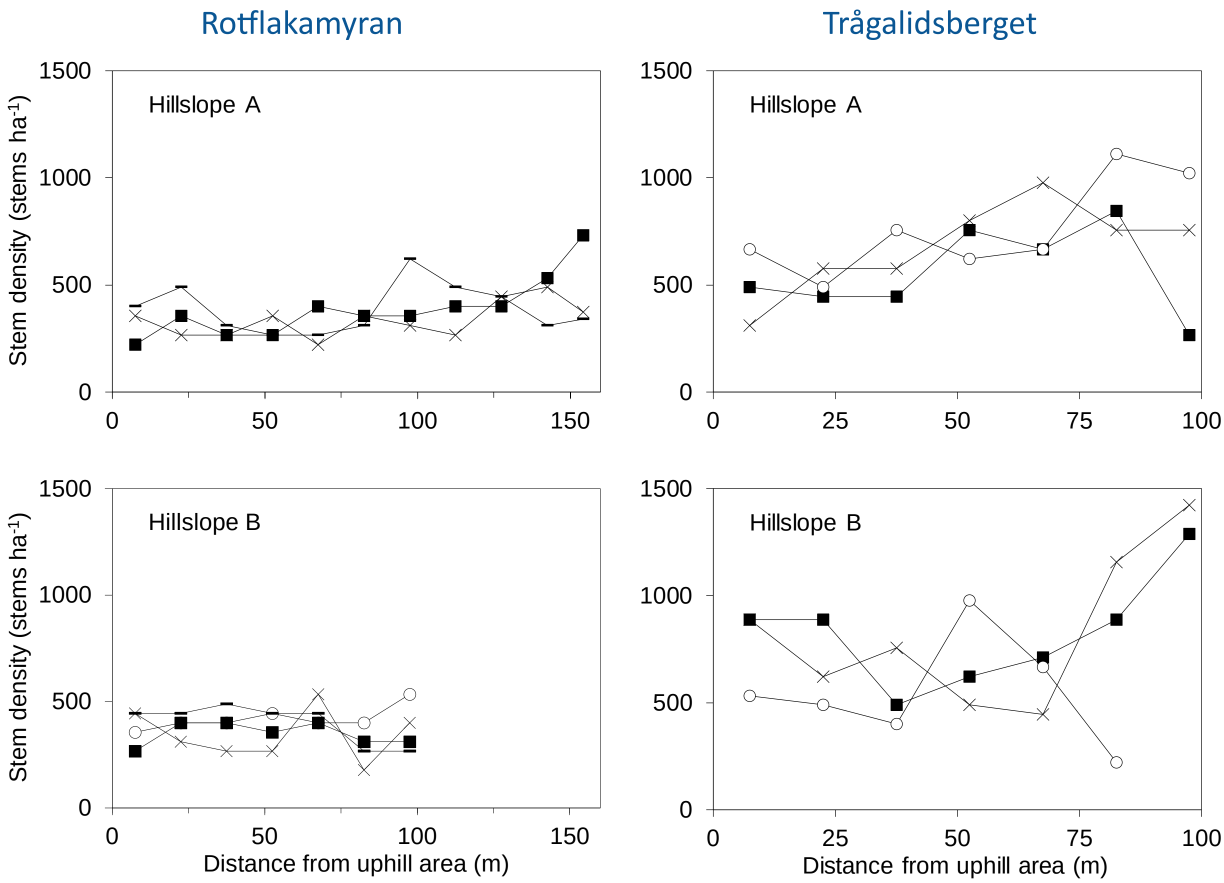


Fig. 9. Stem density of the harvested stands along hillslopes A and B, respectively, at Rotflakamyran (left) and Trågalidsberget (right). The distance on the x-axis refers to the centre of the inventoried subplots, sized 15 m × 15 m, from the uphill area. ○: Ctrl, ■ : No protection, ✕: Logging residue, ‒ : Logging mats.

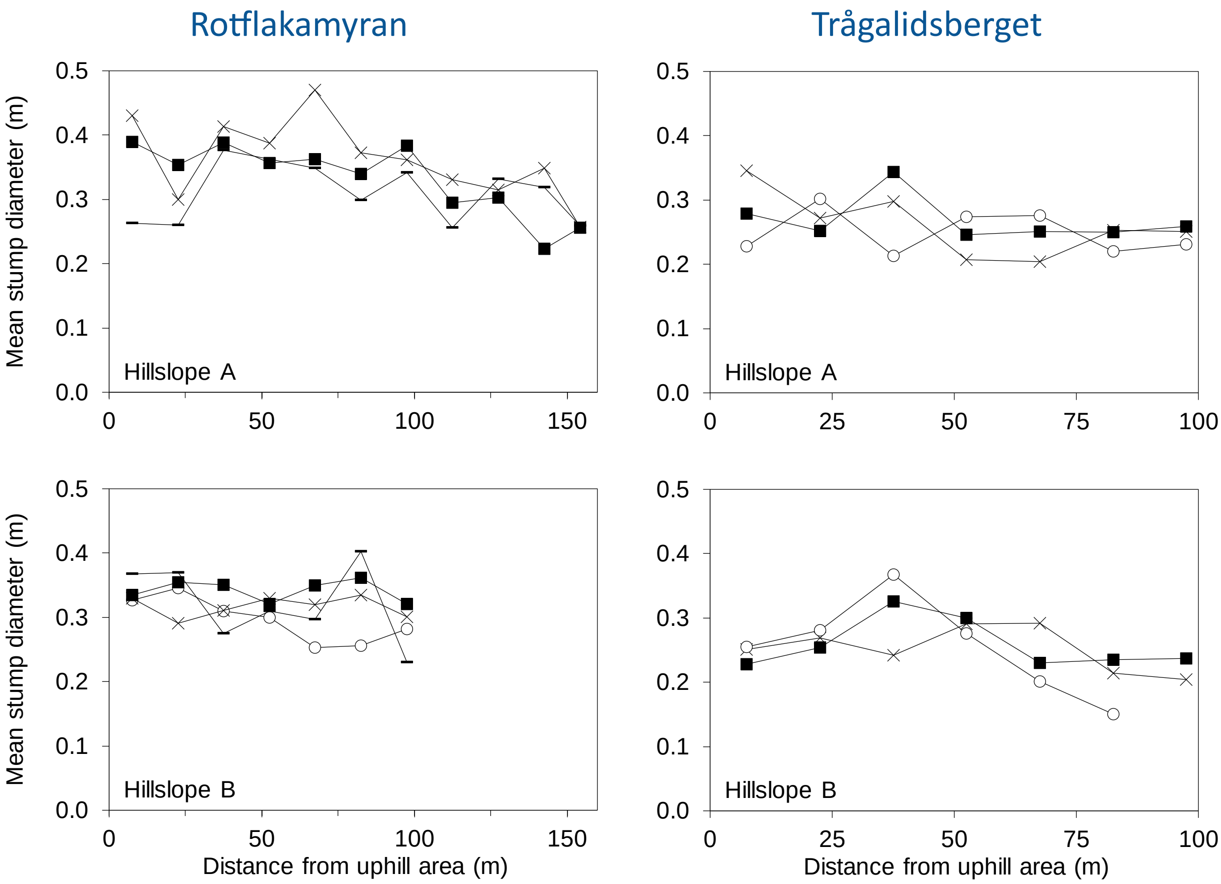


Fig. 10. Mean stump diameter of the harvested stands along hillslopes A and B, respectively, at Rotflakamyran (left panel) and Trågalidsberget (right panel). The distance on the x-axis refers to the centre of the inventoried subplots, sized 15 m×15 m, from the uphill area. ○: Ctrl, ■ : No protection, ✕: Logging residue, ‒ : Logging mats.

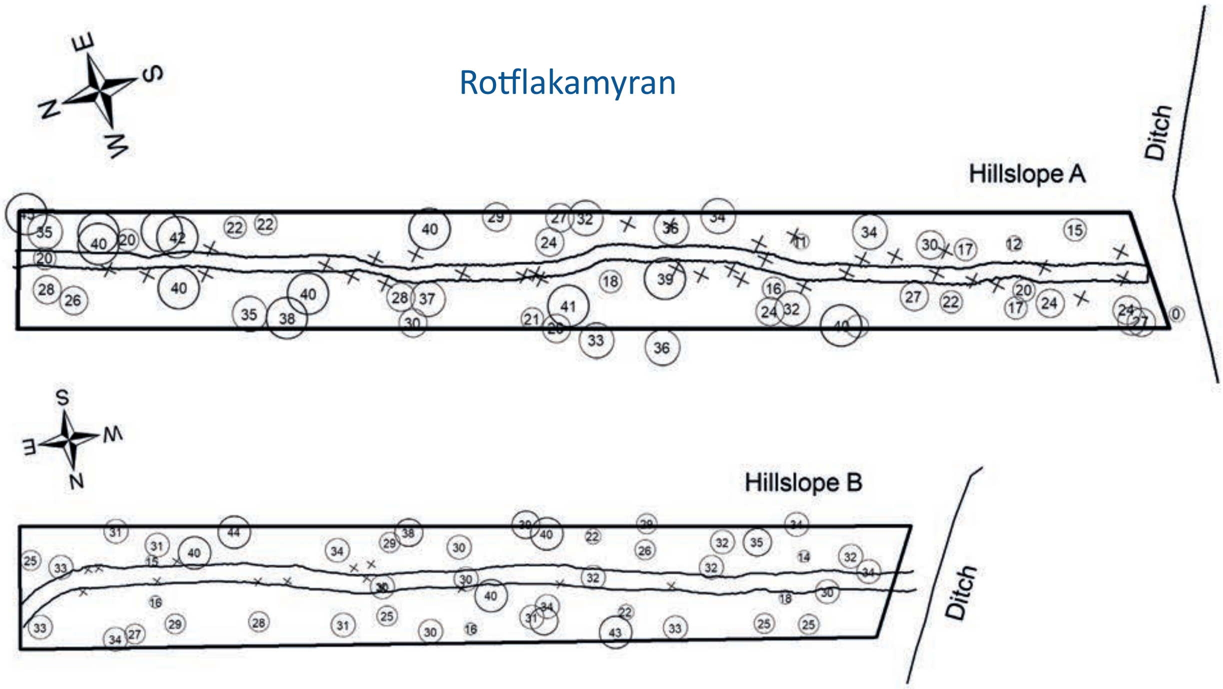


Fig. 11. Locations and diameters of stumps, with a diameter greater than 10 cm, on the study plots without ground protection at Rotflakamyran hillslopes A and B. The start line is to the left. “×” indicates stumps without diameter measurements. The solid lines on the study plots show the forwarder’s wheel tracks.

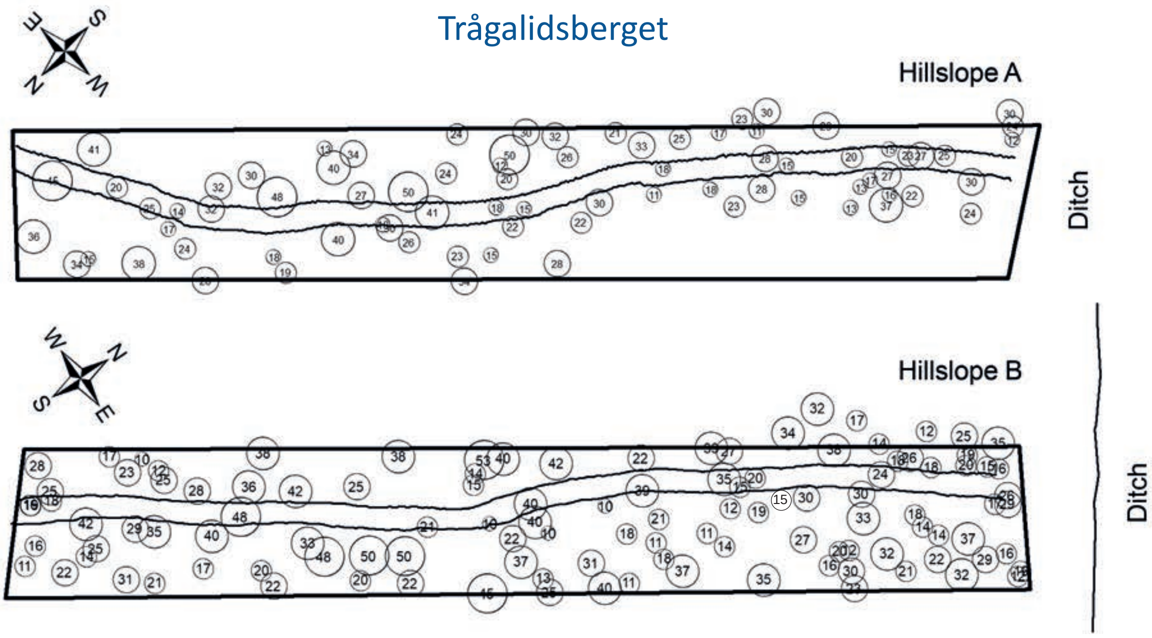


Fig. 12. Locations and diameters of stumps, with a diameter greater than 10 cm, on the study plots without ground protection (NoProt) at Trågalidsberget hillslopes A (adjacent to the wheel tracks) and B. The start line is to the left. The solid lines on the study plots show the forwarder’s wheel tracks.

SOIL TEXTURE

Soil samples were collected from 0-20 cm depth in the mineral soil from transects 1-6 in the control plots and from transect 4 in the remaining plots (Figs. 2-7). The samples were collected using a soil corer with a diameter of 27 mm. Six samples were collected along each transect and combined to form one composite sample which was analysed for textural composition according to ISO 11277:2009 (International Organization for Standardization, 2009). At Trågalidsberget hillslope A, samples were collected only from transects 3-6, due to the large number of stones in transects 1 and 2.

The textural composition of the soil showed little variation along the hillslopes at Rotflakamyran, while a shift in composition was indicated at Trågalidsberget (Fig. 13). Here, the content of finer soil fractions tended to be higher in lower parts of the hillslope. Furthermore, a diagonal gradient in soil texture was suggested across hillslope B (Fig. 14). The organic content for the mass fraction of particles less than 2 mm, measured as loss on ignition (at 550°C), generally varied between 3 and 7% for both sites.

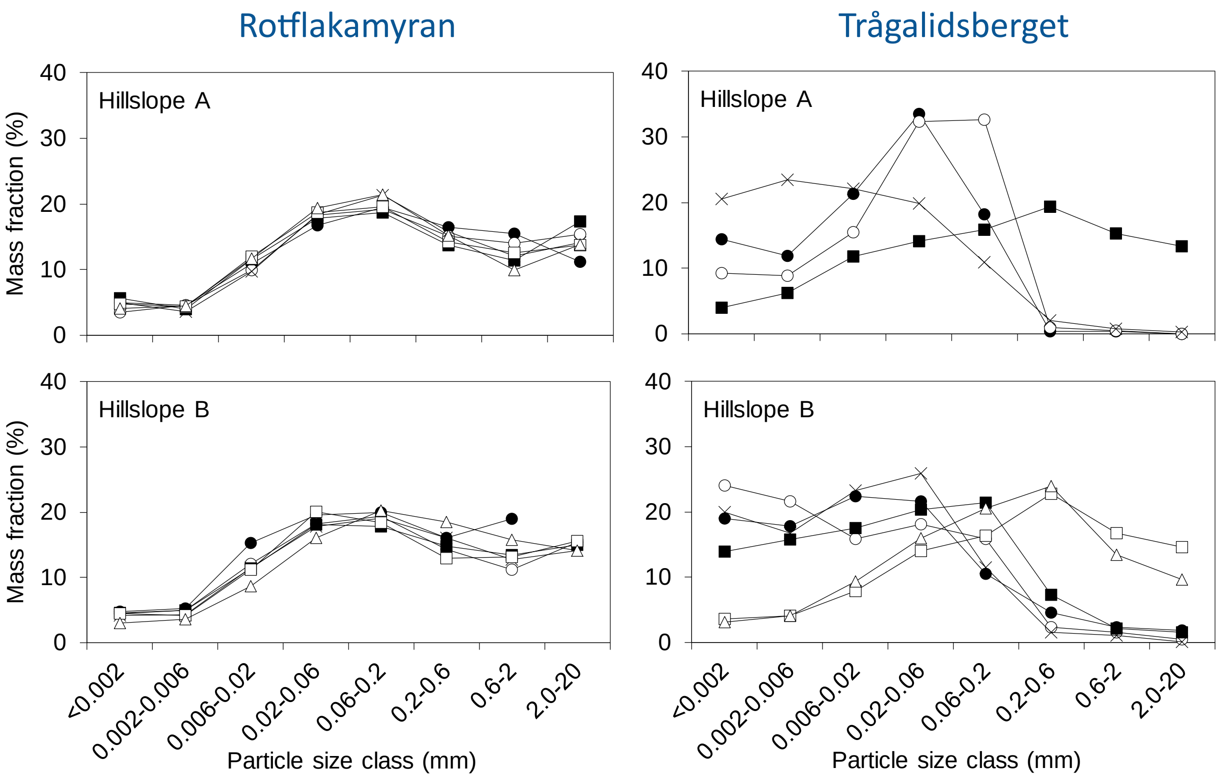


Fig. 13. Mass fraction of eight particle size classes in the mineral soil at 0 to 20 cm depth at Rotflakamyran and Trågalidsberget. The analysed soil samples were collected in the control plots along transects 1-6 (T1-T6). At Trågalidsberget hillslope A, a large number of stones prevented sampling of transects 1 and 2. △: T1, □: T2; ■ : T3, ✕: T4, ○: T5, ●: T6.

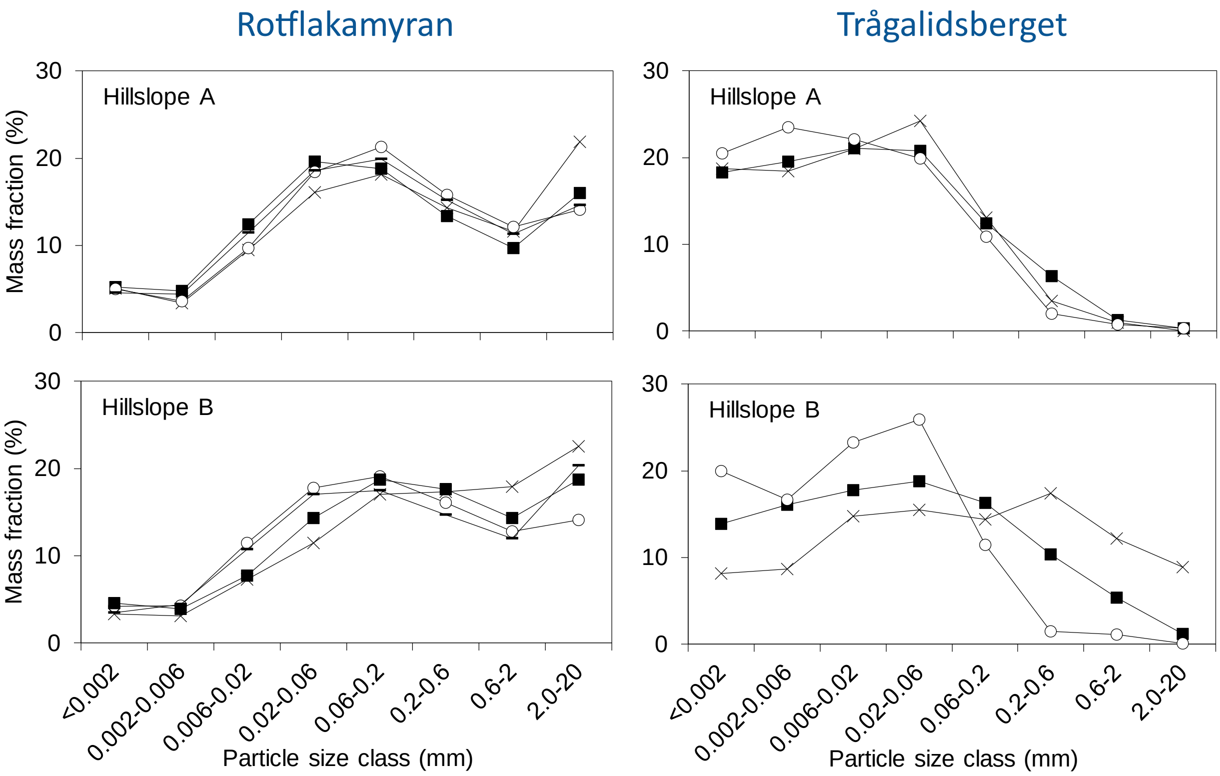


Fig. 14. Mass fractions of eight particle size classes for the mineral soil at 0 to 20 cm depth for transect 4 (T4) at Rotflakamyran (left panel) and Trågalidsberget (right panel). ○: Ctrl, ■: No protection, ×: Logging residue, –: Logging mats.

SOIL PENETRATION DEPTH

The soil penetration depth was defined as the distance between the soil surface and the depth to which a probe could be inserted vertically by hand. Soil penetration depth was used as a simple estimate of the load-bearing capacity of the soil. Two types of probes were used: 1) a metal probe with a diameter of approx. 10 mm, and 2) a cone penetrometer (Eijkelkamp penetrologger with a cone area of 3.3 cm² and 30° angle). At Rotflakamyran, the depth to which the metal probe could be inserted was registered in four classes, including two distinct classes <0.2 m and >0.2 m and two intermediate classes (the results of which were difficult to interpret and are therefore not presented). The actual depth was registered at Trågalidsberget. The depth obtained using the cone penetrometer was the maximum depth at insertion. The cone penetrometer data were collected along transects 1-6 (Figs. 2-7), from six points per transect. However, the data are incomplete because the device broke down during collection.

The metal probe was inserted at nine points on a three-by-three rectangular grid in subplots sized 15 m×15 m (the same subplots used for the stump inventory). As for the stump inventory data, the metal probe insertions depths represent not only the study plots, but may also represent adjacent areas uphill and downhill. Therefore, caution must be taken when comparing these data with other data since the starting points may have differed. The metal probe insertions were carried out in June 2012. The cone penetrometer recordings were performed at the time of treatment, i.e. in June of 2012 and 2013.

At Rotflakamyran, no clear trends in metal probe penetration depth were discernible along the hillslopes (Fig. 15). At Trågalidsberget, the metal probe insertion depth started to increase at about 60 m from the start line and then gradually increased downslope (Fig. 16). In the lower 30-45 m of hillslope B with fine-textured soil, a definite stop for insertion was not observed in many cases. Therefore, the insertion depths for the downslope 30 or 45 m, with the greatest insertion depths, presented in Fig. 16, are underestimated.

At Rotflakamyran, the cone penetration depth showed moderate variation across transects 1-6 (Fig. 17). At Trågalidsberget hillslope B, a sharp change in depth was indicated. Both type of probes gave a similar overall picture of the soil insertion depth along the hillslopes, although the actual depths tended to differ. Thus, no clear trends were detected at the Rotflakamyran hillslopes while there were noticeable differences in penetration depth at Trågalidsberget.

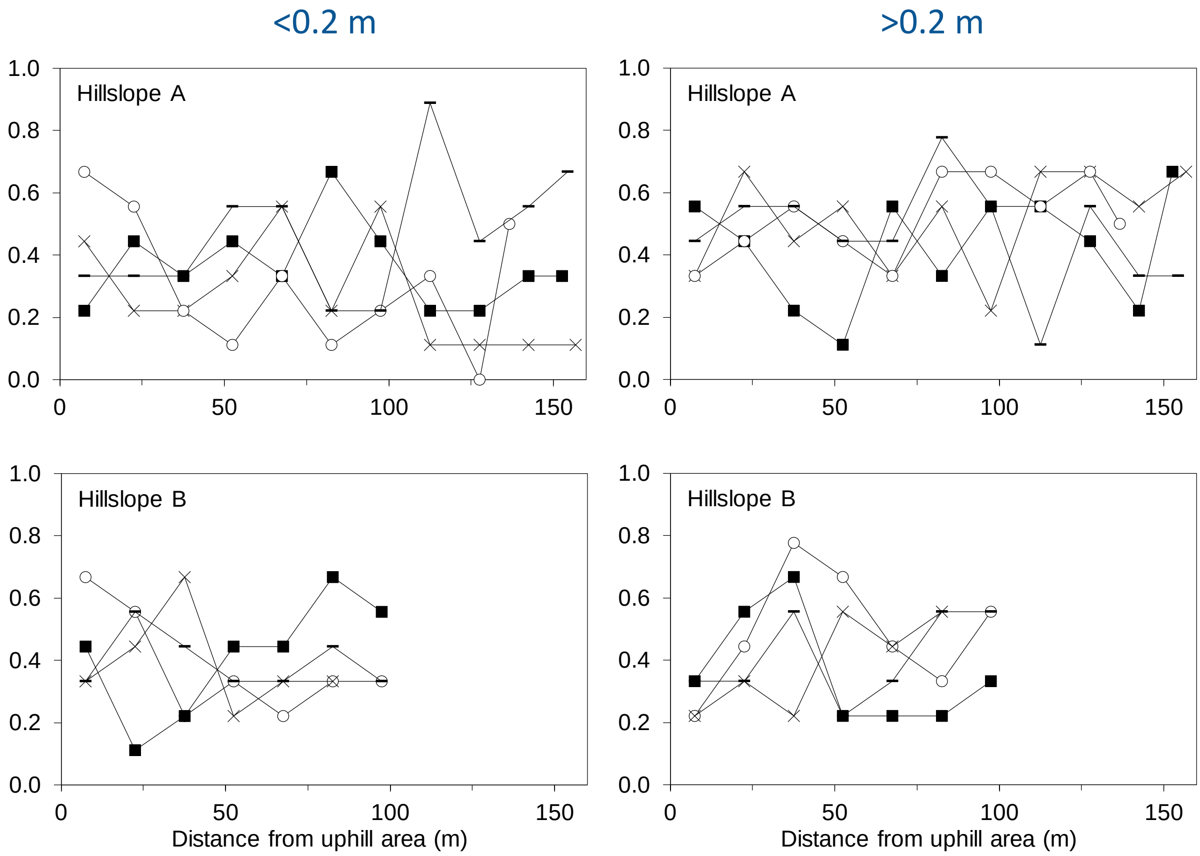


Fig. 15. Proportion of metal probe insertions <0.2 m (left) or >0.2 m (right) on the 15 m × 15 m subplots (in total 9 insertions per subplot) for the study plots at Rotflakamyran hillslope A (above) and B (below). The distance from the upslope short side refers to the centre of each subplot. ○: Ctrl, ■: No protection, ×: Logging residue, –: Logging mats.

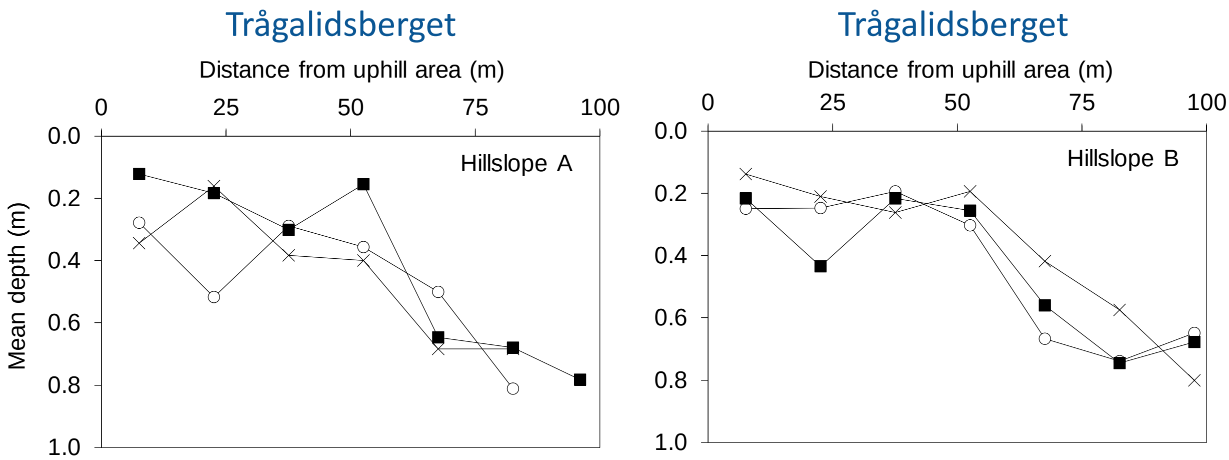


Fig. 16. Metal probe insertion depth along the study plots at Trågalidsberget (mean depth per subplot). The depths presented for the most downhill area (lower 30-45 m) of hillslope B are underestimated because a definite depth could not be determined in many cases. ○: Ctrl, ■: No protection, ×: Logging residue.

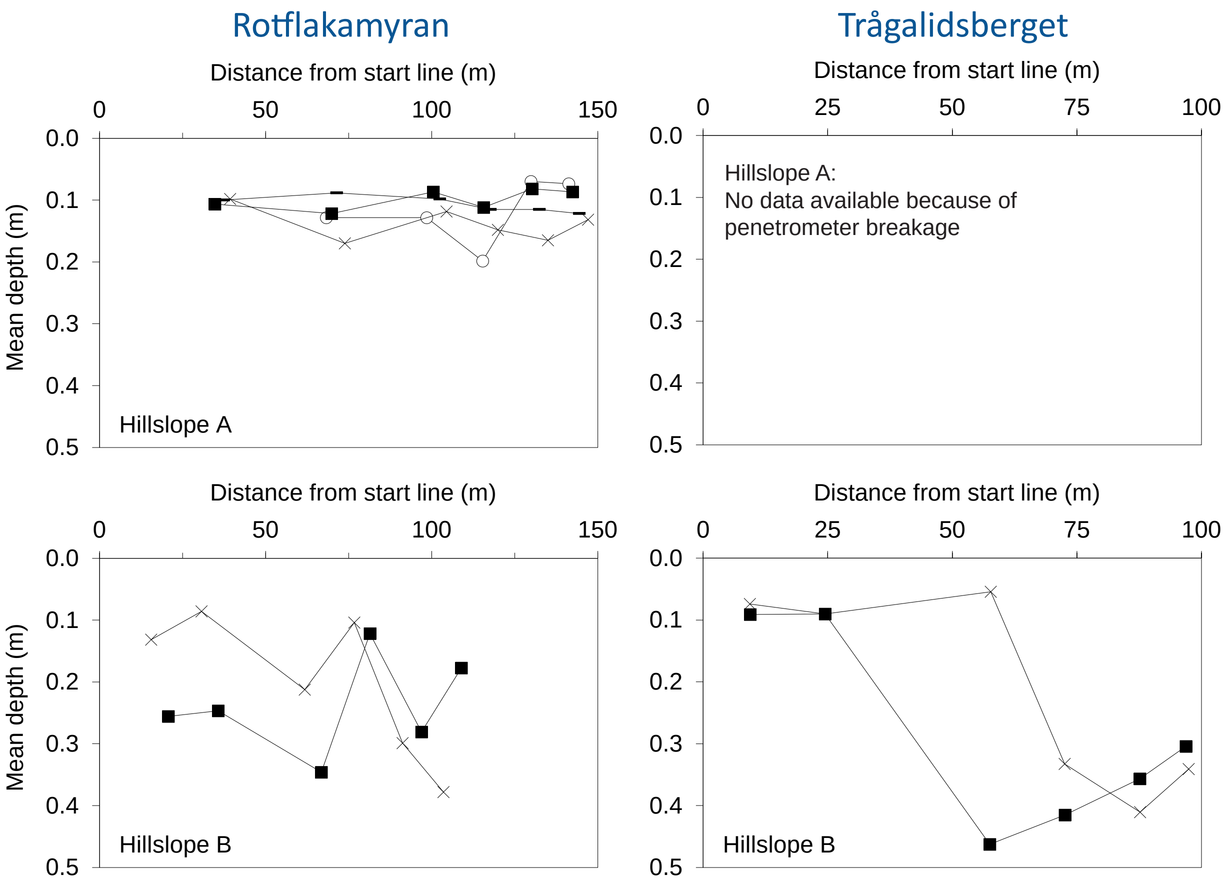


Fig. 17. The mean maximum cone penetration depth at Rotflakamyran (left) and Trågalidsberget (right) before treatment. Six measurements per transect were performed along T1-T6 at Rotflakamyran hillslope A and 12 measurements per transect for hillslope B at both sites. ○: Ctrl, ■: No protection, ×: Logging residue, –: Logging mats

Experimental design

The sites had a randomized block design with two hillslopes (blocks) hosting three or four study plots subjected to different driving treatments with a laden forwarder (Figs. 2-3). To avoid driving on the plots before treatment, the plots were established before logging, in areas without visible signs of former traffic. The Rotflakamyran site was harvested during December 2011 and the Trågalidsberget site during February 2012. At logging, the harvester and the forwarder were allowed to drive only on extraction routes between the plots. These routes were heavily reinforced with logging residue to avoid rutting. The logging residue on the extraction routes was left permanently on site, while residue remaining from the harvest was removed from the study plots.

The study plots were established in the forest (before harvesting) using a measuring tape and a sighting compass. The downslope short side was laid out in parallel with the ditch located at the bottom of the hillslopes. Therefore, the downslope short side did not always meet the long side at right angles (Figs. 2-7). After treatment, GNSS-positioning of the installations, study plots and ruts was undertaken using a handheld GNSS-receiver, model Topcon GRS-1 (http://www.topconpositioning.com/) (Figs. 2-7). A common start line was defined uphill for each block based on the GNSS-positioning (Figs. 2-3). The start line is orthogonal to the long sides of the study plots. For Trågalidsberget hillslope B, this resulted in a mismatch between the start line and the positions of the short sides for the control and logging residue plots (Fig. 7).

DRIVING TREATMENTS

The treatments consisted of driving a laden forwarder (pictured in Fig. 18) along the clearcut hillslopes, on the study plots, with or without ground protection. Due to substantial rainfall shortly before the treatments were carried out, the soil was wet at the time of treatment. In total, six passes were performed except on the downhill part of two study plots where deep rutting prevented further traffic. At Rotflakamyran, the treatments were carried out on 7-8 June (hillslope A) and 11 June (hillslope B) in 2012. At Trågalidsberget, the treatments were performed on 19 June (hillslope A) and 18 June (hillslope B) in 2013. At this site, one additional plot was established on each hillslope (Extra plots A and B) without ground protection (Fig. 3). These plots were not part of the randomized block design. Extra plot A was subjected to four passes and Extra plot B six passes by the laden forwarder. The driving treatments will be described in detail in a future publication by Ring *et al*. The ground protection used was logging residue or logging mats (Figs. 19-20). The treatment with logging mats could not be carried out at Trågalidsberget, because transportation of the mats from the landing to the study area would have required multiple crossings of a sensitive area with low bearing capacity adjacent to a stream.

Fig. 18. The treatments were performed using a John Deere 1410D forwarder with eight wheels and 710 mm wide tires with a tire pressure of 350 kPa and 500 kPa for the tractor and wood bunk, respectively. Bogie tracks were mounted both on front (Olofsfors ECO-TRACKS) and rear (Clark Terra Lite) wheel pairs. The forwarder was operated by the same driver at both sites. Photo Eva Ring

Fig. 19. Above: The logging residue was applied by the forwarder, starting uphill and moving downwards. The photo shows the application on hillslope A at Rotflakamyran. Below: Logging mats stored at the landing awaiting application. One mat consisted of five planed stems mounted together, measuring approx. 5 m × 1 m × 0.2 m and weighing 500-600 kg. Photo Eva Ring

Fig. 20. Rotflakamyran hillslope A. Above: Placement of logging mats from the forwarder wood bunk using the boom-mounted grip. Below: Driving on the mats – view from the forwarder cabin. Photo Eva Ring

REGENERATION

A study of how the different driving treatments affect regeneration began in 2014. One-year old containerized *P. sylvestris* seedlings, pre-treated with Merit Forest to reduce pine weevil (*Hylobius abietis*) damage, were planted on the study plots without site preparation in June 2014. The seedlings were planted at fixed distances from the ruts: Position 1—ca 4 m from the outside border of the rut, Position 2—ca 2 m from the outside border of the rut, Position 3—1 dm from the outside border of the ruts, Position 4—in the centre of the rut, and Position 5—between the left and right ruts (Fig. 21). The distance between seedlings within plant rows was approximately 2 m. Additional seedlings were planted to allow harvest of some seedlings. In the control plots (without forwarder traffic), seedlings were planted at 2-m intervals.

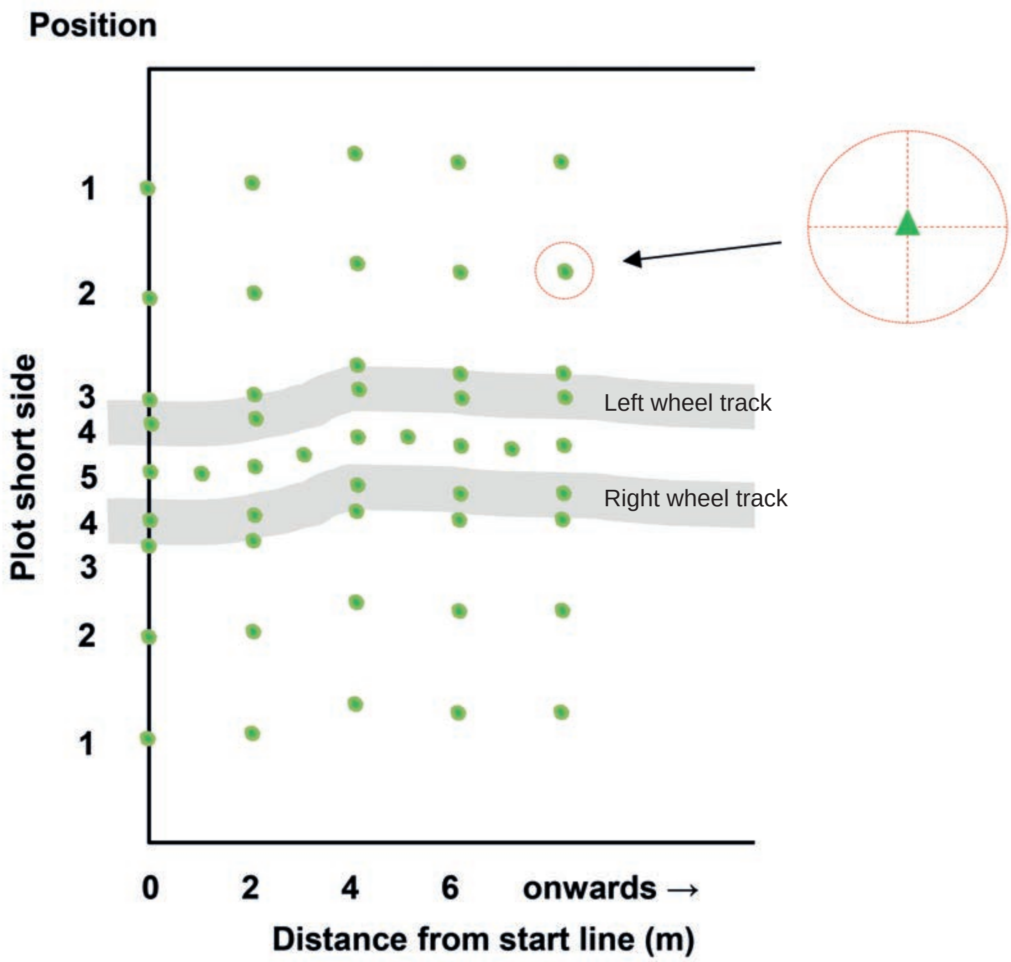


Fig. 21. Schematic outline of the planting positions (green circles) on the upper part of a study plot. The red circle (Ø=0.6 m) shows the circle sectors within which the characteristics of the seedling root system were assessed for the seedlings harvested in 2018. An inventory of the ground vegetation was carried out in 2017 between positions 1 and 2 every 10th meter along the entire study plot representing the treatment with no ground protection (Hansson *et al.*, 2019).

Data collection

METEOROLOGICAL DATA

Meteorological measurements were carried out at both study sites. At Rotflakamyran hillslope A, precipitation, air temperature, relative humidity, wind speed and insolation were measured. Precipitation and air temperature were measured at Rotflakamyran hillslope B and Trågalidsberget hillslope A. Reliable data on precipitation could be obtained only for precipitation falling as rain.

The equipment used was mainly from Campbell Scientific (https://www.campbellsci.com/). At Rotflakamyran hillslope A, a logger system was installed comprising a CR10X logger, a tipping bucket rain gauge (ARG100 at 0.6 m height), a combined temperature and relative humidity probe (Rotronic HygroClip Relative Humidity and Temperature Probe HC-S3 at 2.03 m height), a pyranometer (LI-COR SZ200 at 1.8 m height), and a three-cup anemometer (A100R at 2.0 m height) (Fig. 22). At Rotflakamyran hillslope B and Trågalidsberget hillslope A, a tipping bucket rain gauge (ARG100 at a height of 0.8 m at both sites) and a temperature probe (Campbell Scientific 107) at a height of 2.08 m on Rotflakamyran hillslope B, and 1.9 m at Trågalidsberget hillslope A) were connected to a CR510 logger. Data was collected at 1- or 2-hour intervals.

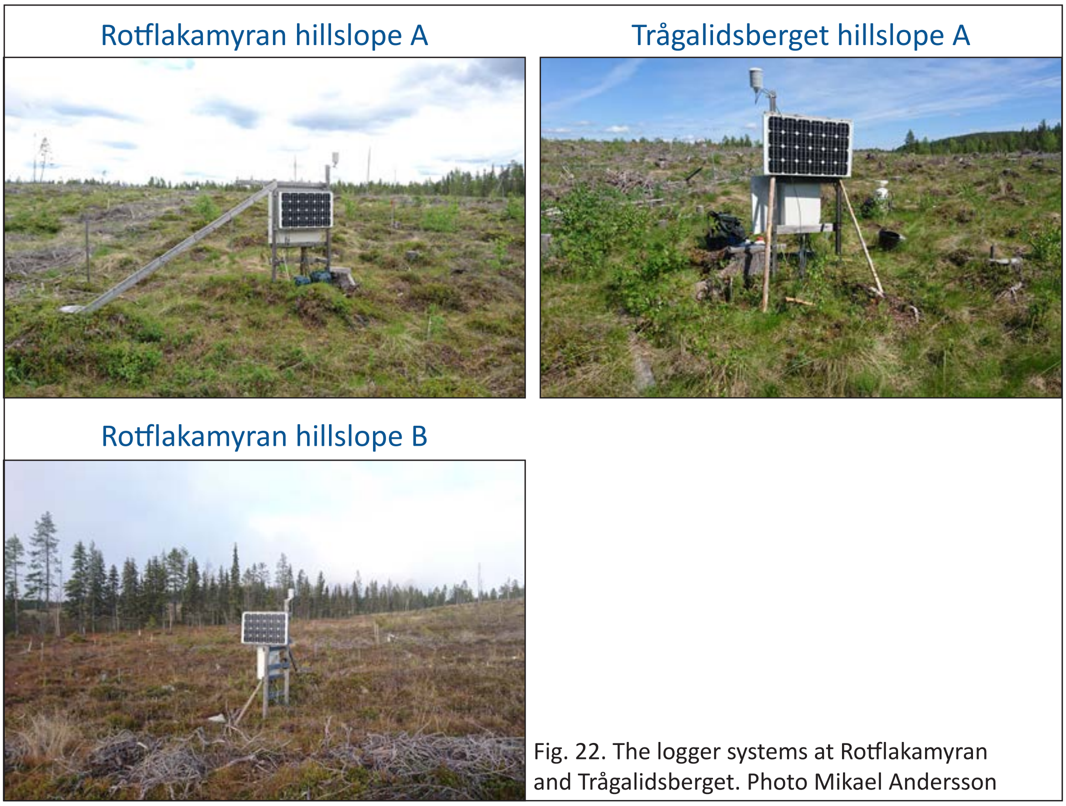


Fig. 22. The logger systems at Rotflakamyran and Trågalidsberget. Photo Mikael Andersson

GROUNDWATER LEVELS

Groundwater tubes were installed in the lower part of the study plots (Figs. 4-7). At Rotflakamyran, the installations were performed in August and September, 2012, and at Trågalidsberget in June, 2013. The tubes (1.2-m long PVC tubes with 27 mm inner diameter) were installed in the area between the left and right wheel tracks, at a depth of 0.6-1 m (Figs. 23-24). In the control plots (without driving), the tubes were installed in the centre of the plots. On the plots with four groundwater tubes, the two tubes furthest uphill were difficult to install because the soil became very compacted at a depth of about 0.7 m. A water height probe (TruTrack WT-HR 1000, https://www.trutrack.com/) was inserted in the groundwater tubes except in the plots with Campbell loggers (Fig. 23). In the latter plots, three CS450 pressure transducers (https://www.campbellsci.com/) were installed and connected to the logger (Fig. 23). During May-June of 2014, the 1.2-m long groundwater tubes on the plots with four groundwater tubes (for monitoring the groundwater level) were replaced by 2-m long tubes to allow monitoring at frost-free depth all-year round (Figs. 4-7). The installation of the 2-m long tubes was performed using a Berema pionjär BR120 petrol breaker and the tubes were installed at 1.5-1.8 m depth. Additional tubes for groundwater sampling (as part of a study of mercury) were installed at both sites in June 2013 (Fig. 24).

Fig. 23. Equipment used for monitoring the groundwater level: a groundwater tube with bottom cap (left), a 1-m long water height probe (TruTrack WT-HR 1000) installed in a groundwater tube (centre), and a pressure transducer (Campbell CS450) (right). Photo Eva Ring

Fig. 24. Left: A groundwater tube in the study plot with no ground protection at Trågalidsberget hillslope B (in the downhill area). Right: A groundwater tube with a CS450 pressure transducer mounted using an open/ventilated T-coupling (lower left) and a tube used for groundwater sampling (with the longest aboveground tube length). Photo Eva Ring

GROUNDWATER AND SOIL CHEMISTRY

Groundwater samples were collected in 2012, 2013 and 2014 from the two hillslopes at Rotflakamyran to determine levels of total mercury (THg) and methyl mercury (MeHg). At Trågalidsberget, the groundwater tubes were most often dry at the time of sampling and no samples could be collected. Groundwater samples were collected from groundwater tubes located in the lower part of the hillslopes in all treatment plots at Rotflakamyran. During sampling, all equipment used (vacuum chamber, tubes and bottles) as well as the groundwater tube itself was flushed with nitrogen gas before and during the sampling to obtain oxygen free conditions. Samples were analysed for MeHg at Umeå University and for THg at Stockholm University.

Soil samples were collected using a soil coring tube, with a diameter of 23 mm, in late summer 2016 and 2017 for analyses of THg, total carbon (TC) and total nitrogen (TN). Samples were collected from the upper 5 cm of the O horizon, or the whole O horizon if the depth of the O horizon were less than 5 cm. When an O horizon was lacking (most often in the plots without ground protection), the upper 5 cm of the soil, independent of horizon, were sampled. Samples were collected at both sites in the plots representing the treatments no driving, driving without ground protection and driving on logging residue, at four distances from the downhill plot´s short side. In total, 12 samples were collected from each hillslope on each sampling occasion. In the plots with logging residue, the soil beneath the logging residue was sampled. All samples were placed in LDPE (Low Density Polyethylene) bottles and stored on dry ice in a cooler until reaching the laboratory, where they were stored at -18°C until freeze-drying. After freeze-drying, the samples were homogenized using a mortar and pestle. THg analyses were carried out at the Department of Aquatic Sciences and Assessment, SLU, using a Perkin Elmer SMS100 instrument following US EPA method 7473 (2007). TC and TN were determined at the Department of Soil and Environment, SLU, on freeze-dried and homogenized soil samples following standard method ISO 10694 (TC) and ISO 13878 (TN).

RUT DEPTH

The rut depth was measured manually by placing an aluminium profile across an individual rut and measuring the vertical distance to the deepest point of the rut with a ruler. In the case of lateral bulging, the aluminium profile was placed to measure the undisturbed soil surface.

Rut depth was measured at 1-m intervals in June 2013, one year after treatment at Rotflakamyran and one day after treatment at Trågalidsberget. At Rotflakamyran, rut depth was also measured four days after treatment in 2012, at 2-m intervals (Table 1). In addition to the manual measurements described, rut depth was also assessed using GNSS-positioning.

In the study plots with logging residue or logging mats, there was less rutting than in the plots with no ground protection (Figs. 25-26). The rutting in the plots with logging mats occurred mainly because the mats tilted on boulders or stones or the forwarder slipped off the mats (Figs. 27-28).

Fig. 25. Rutting on the study plots subjected to forwarder traffic with no ground protection at Rotflakamyran one day (hillslope A) and two months (hillslope B) after treatment. Above: Rutting in the upper part of the hillslopes (defined as “0 cm” when measured manually). Below: Rutting in the lower parts –all views are downhill. Photo Eva Ring

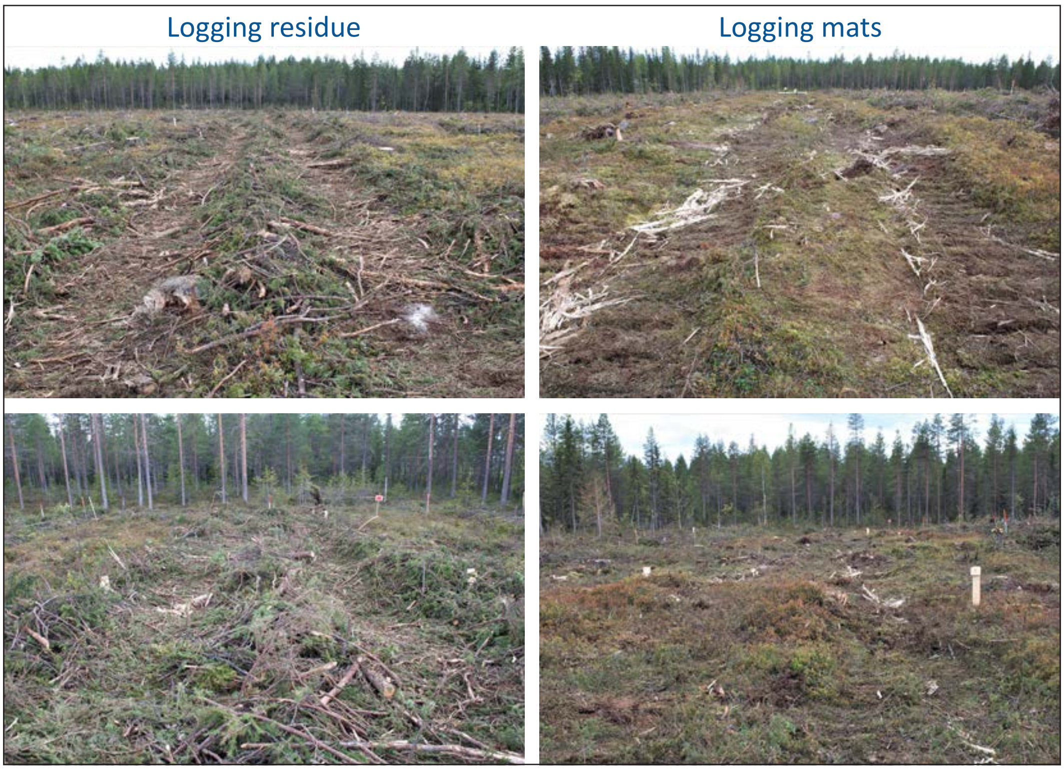


Fig. 26. Wheel ruts in the study plots where logging residue (left) and logging mats (right) was used for ground protection one day after treatment at Rotflakamyran hillslope A. The upper part (above) and lower part (below) of hillslope A –all views are downhill. Photo Eva Ring

Table 1. Scheme for rut depth measurement at the Rotflakamyran and Trågalidsberget sites, where the driving treatments were carried out in 2012 and 2013, respectively. The depth was measured with a ruler from the bottom of the rut to an aluminium profile placed horizontally across the rut. Where lateral bulging had occurred, the aluminium profile was pressed down to represent the original soil surface. "Year" is the year of measurement. "1 m": depth measured at 1-m intervals, "2 m": depth measured at 2-m intervals.

Treatment	Year	Rotflakamyran		Trågalidsberget	
		Hillslope A	Hillslope B	Hillslope A	Hillslope B
No protection	2012	2 m	2 m	–	–
Logging residue	2012	No rutting observed	No rutting observed	–	–
Logging mats	2012	2 m[a]	2 m[a]	–	–
No protection	2013	1 m	1 m	1 m[b]	1 m[c]
Logging residue	2013	Not measured	Not measured	No rutting observed	Rutting observed in two spots per rut
Logging mats	2013	Not measured	Not measured	–	–

[a] Measurements were made at 2-m intervals and in all places in-between where rutting had occurred.
[b] 2-m intervals were used on Extra plot A.
[c] 1-m intervals were used on Extra plot B.

REGENERATION

Seedling height and diameter was measured once a year in 2014, 2015, 2016 and 2018. On these occasions, seedling survival and damage were also registered. In 2018, eight seedlings per position, treatment and site were harvested. For the harvested seedlings, biomass, both below and above ground, and the nitrogen content of the needles were measured. To investigate the development of the seedling root system, the number of roots and root length were measured in a circle with a diameter of 0.6 m (Fig. 21). Also, needle $\delta^{13}C$ was analysed to indicate potential water stress.

Fig. 27. Rutting in the study plot with logging mats at Rotflakamyran hillslope A, caused by the forwarder slipping off the mat. The photo also shows the forwarder when removing the mats after driving, starting downhill and moving uphill. Photo Eva Ring

Fig. 28. Driving on logging mats applied on uneven ground resulted in significant wear of the mats. Photo Eva Ring

Concluding remarks

The Rotflakamyran and Trågalidsberget sites are representative of significant areas of productive forest land in this region. The till soils with a high content of stones and boulders in uphill areas are common on forest land (Stendahl *et al.*, 2009; MarkInfo, https://www.slu.se/miljoanalys/statistik-och-miljodata/miljodata/webbtjanster-miljoanalys/markinfo/markinfo/). The variations in soil type and topography within a site or forest compartment play an important role in determining the load-bearing capacity of the soil (Mohtashami *et al.*, 2017). This type of variation was captured by the set-up at the Rotflakamyran and Trågalidsberget sites, with hillslopes starting in well-drained areas upslope (groundwater recharge areas) and ending in wet areas downslope (groundwater discharge areas). While recognizing this large-scale variation, the variation within each hillslope should be as small as possible to allow valid comparisons between the study plots on each hillslope. In fact, the variation among the study plots within each of the hillslopes generally seemed small, possibly with the exception of Trågalidsberget hillslope B where a gradient in soil textural composition was suggested across the hillslope. Results from the two sites have already revealed interesting insights into the environmental impact of forwarder traffic (Ågren *et al.*, 2015; Hansson et al., 2018; Hansson *et al.*, 2019). As such, we believe that the Rotflakamyran and Trågalidsberget sites have great potential to host new projects and generate valuable data for forestry, society and researchers over the coming decades.

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