INSTITUTE OF FOREST ENGINEERING
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WHOLE-TREE CABLE YARDING

IMPACT OF

TOPPING TREES AND RETURNING SCREENING REJECTS

ON BIOMASS AND NUTRIENT REMOVAL

DISSERTATION

in fulfillment of the requirements for the degree of
doctor naturalium technicarum (Dr. nat. techn.)

submitted by
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On April 7, 2015, Karl Stampfer commissioned me to work on projects dealing with different strategies in cable yarding, which aim to ensure a nutrient sustainable forest management by reducing nutrient exports from the forest sites.

As a young researcher, I could not have wished for a better and more interesting assignment. It required to get in contact with forest enterprises, discussing new ideas and looking for ways to integrate them into current harvesting operations.

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Abstract

Whole-tree (WT) harvesting has become the most common harvesting method in cable yarding, but questions remain regarding its long-term sustainability. Hence, the main purpose of this thesis was to analyze methods, which aim to minimize nutrient export from the forest sites in an economically reasonable way. In particular, the present thesis focuses on an already applied approach (topping of trees in WT-cable yarding) and a new approach (returning screening rejects with a prototype spreader along a cable corridor).

The first two publications aim to analyze the efficiency and effectivity of topping trees in cable yarding. Biomass models for Norway spruce have been developed in order to estimate the implications of using different topping diameters on biomass and nutrient removal. In addition, time studies were conducted to estimate the influence of topping on system productivity. The results showed that topping of trees is an effective way to decrease nutrient losses in WTH. The magnitude of nutrient removal significantly depends on the developmental stage of the stand and the topping diameter. Results showed that the effect of topping trees is largest in the thinning of young stands due to the high number of removed (and topped) trees. Productivity analyses showed that topping trees only leads to a significant loss in productivity if the trees get topped during extraction.

Publication III and IV focus on the separation of nutrient-rich components within logging residue woodchips in order to return them to forest sites as a nutrient source. A mobile star screen was used to increase the quality of the screened logging residue woodchips by rejecting fine and oversize particles. Subsequently, the fine particles were spread onto steep terrain slopes by a modified centrifugal spreader. Analyzes showed that screening is able to substantially improve material characteristics like ash content and particle size distribution. However, productivity of the spreader was rather low (145-320 kg_{atro}/PSH_{15}) and significantly depended on the moisture content of the material.

List of publications

The following four papers, which will be referred to in the text by Roman numerals, constitute the basis for this thesis:

Publication I **Effect of topping trees on biomass and nitrogen removal in the thinning of Norway spruce stands.**

Christoph Huber, Maximilian Kastner, Eduard Hochbichler, and Karl Stampfer
Sustainability, 9(10) (2017) 1856.

Publication II **Efficiency of topping trees in cable yarding operations.**

Christoph Huber, and Karl Stampfer
Croatian Journal of Forest Engineering, 36*(2)* (2015) 185-194.

Publication III **Performance of a mobile star screen to improve woodchip quality.**
Christoph Huber, Huberta Kroisleitner, and Karl Stampfer
Forests, 8(5) (2017) 171.

Publication IV **Evaluation of a modified centrifugal spreader to apply nutrient-rich fine fractions from woodchips as a fertilizer to cutover areas in steep terrain.**

Christoph Huber, and Karl Stampfer
Proceedings of the 39th Annual Meeting of the Council of Forest Engineering (COFE), Vancouver, Canada, 22-24 Sept. 2016.

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Synthesis

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Introduction

1.1 Problem statement

In Austria, whole-tree harvesting (WTH) has become more common in steep terrain harvesting during the last few decades. From an economical point of view, WT-cable yarding is the only practical option for most steep slope sites. The main reason for the increased popularity of this harvesting system is the development of so-called processor-tower yarders in the late 1970s (Heinimann et al. 2006). These tower yarders are equipped with boom-mounted processors, which allow them to work cost-efficiently in WTH. Heinimann et al. (2006) estimated that the use of processor-tower yarders resulted in cost-savings of approximately 40% compared to motor-manual cut-to length (CTL) cable yarding.

Other reasons for the increased popularity of WTH in cable yarding are (1) the perpetual lack of qualified, skilled workers and (2) the growing interest in using woody biomass for energy production. The European Commission has set a target to achieve a share of renewable energy of 20% by 2020 (Peltola et al. 2011). In order to achieve this goal, woody biomass from forests is considered as an important energy resource (Verkerk et al. 2011). As a result, the demand for energy wood is increasing continuously (Wall 2012), which again promotes the use of WTH due to higher revenues for traditionally unmarketable byproducts like treetops and branches.

Although the utilization of forest biomass is considered beneficial as a substitute for fossil fuels, there are also negative impacts which need to be considered. In WTH operations, nutrient removal from the harvesting site is substantially larger than in CTL operations due to the extraction of nutrient-rich crown material (branches, foliage). As a result, concerns about the sustainability of WTH have been raised by many researchers since the late 1960s (e.g. Krapfenbauer 1968; Kreutzer 1980; Sterba 1988). Numerous studies on the impacts of WTH on site productivity (e.g. Egnell and Leijon 1997, Mälkönen 1976, Kimmins 1977) and tree growth (e.g. Helmisaari et al. 2011, Sterba 1988, Proe and Dutch 1994) have been conducted. The majority of these studies conclude that WTH is capable of reducing tree growth and site productivity in the long-term. However, there are still uncertainties about the magnitude and durability of the negative impacts on site fertility as no empirical data is available over multiple rotation periods.

One possibility to limit the negative impacts of WTH operations to an acceptable level is to apply nutrients to forest sites. Since the late 1960s, many studies on forest fertilization were conducted in North America (e.g. Page and Gustafson 1969, Kvamme 1979, Barker 1979), which mainly focused on aerial distribution of granular or fluid fertilizers by helicopters and airplanes. However, although fertilization is a common praxis in many countries (Miller et al. 2016), the extraction of fertilizers on steep slope forests is of subordinate importance in Central Europe due to high application costs and low public acceptance.

Other studies, conducted both in North America and Europe, focused on wood ash fertilization and liming (e.g. Lundström et al. 2003, Pitman 2006, Väätäinen et al. 2011, Bohrn and Stampfer 2014, Brais et al. 2015). However, although these methods are of higher public acceptance, the importance of wood ash and lime application in steep terrain is very limited because the terrain limits the accessibility by ground-based machinery and thus largely prevents mechanized fertilization. Another disadvantage of using wood ash and lime for forest fertilization is their low content of nitrogen (Bohrn and Stampfer 2014), which is the nutrient most frequently limiting growth on mineral soils in Austria (Englisch and Reiter 2009).

However, although most of the studies conclude that a forest's nutrient budget can be largely influenced by choosing different harvesting methods, only a few studies focused on counteractive measures. At present, there is still an urgent need two implement new methods, which help to decrease the aforementioned disadvantages of WT-cable yarding in an economically reasonable way.

1.2 Objectives

This thesis focuses on analyzing two methods, which aim to reduce the negative ecological impacts of WT-cable yarding. The publications are referred to as Publication I, Publication II, Publication III, and Publication IV in the following.

The first part of the thesis deals with topping trees in WT-cable yarding operations:

- Assessment of the amount of biomass and nitrogen, which remains on-site after WT-cable yarding operations (Publication I).
- Development of biomass models for estimating the additional effect of topping trees at various diameters on the amount of logging residues (Publication I).
- Development of productivity models in order to estimate the effect of topping trees on system productivity (Publication II).
- Assessing the impact of implementing topping strategies on the stress and strain of the chainsaw operator (Publication II).

The second part of the thesis deals with the return of screening rejects from logging residue woodchips to forest sites:

- Assessment of the performance of a mobile star-screen to increase the quality of woodchips by separating nutrient-rich fine materials like needles or branches (Publication III).

- Calculation of the screening costs (Publication III).
- Assessing the suitability of screening rejects in terms of physical and chemical characteristics for returning them to forest sites (Publications III and IV).
- Assessment of the performance and operational costs of a prototype centrifugal spreader, designed to apply screening rejects to harvesting sites (Publication IV).

2

Cable yarding in Austria

2.1 Importance of WT-cable yarding

Austria's forests are characterized by a high proportion of steep terrain. Approximately 22% of the managed forest area is steeper than 60% (Hauk and Perzl 2013). There, ground-based forest machines like harvesters, skidders or forwarders often reach not only their physical, but also their ecological limits due to irreversible damages to the forest soil (rutting, soil compaction, etc.). As a result, cable-based harvesting systems are preferred for steep terrain harvesting. Currently, ca. 20% of the total annual timber cut is extracted by cable-based systems in Austria (BMLFUW 2017). This proportion has only changed marginally during the last 14 years (Figure 1).

At present, tower yarders are mainly used for cable-based harvesting. Until the 1990's, most of the cable yarding was carried out using motor-manual CTL-method. Since then, WT-cable yarding became widely used in Austria and largely replaced CTL-cable yarding due to the increased use of processor tower yarders (see also chapter 1.1).

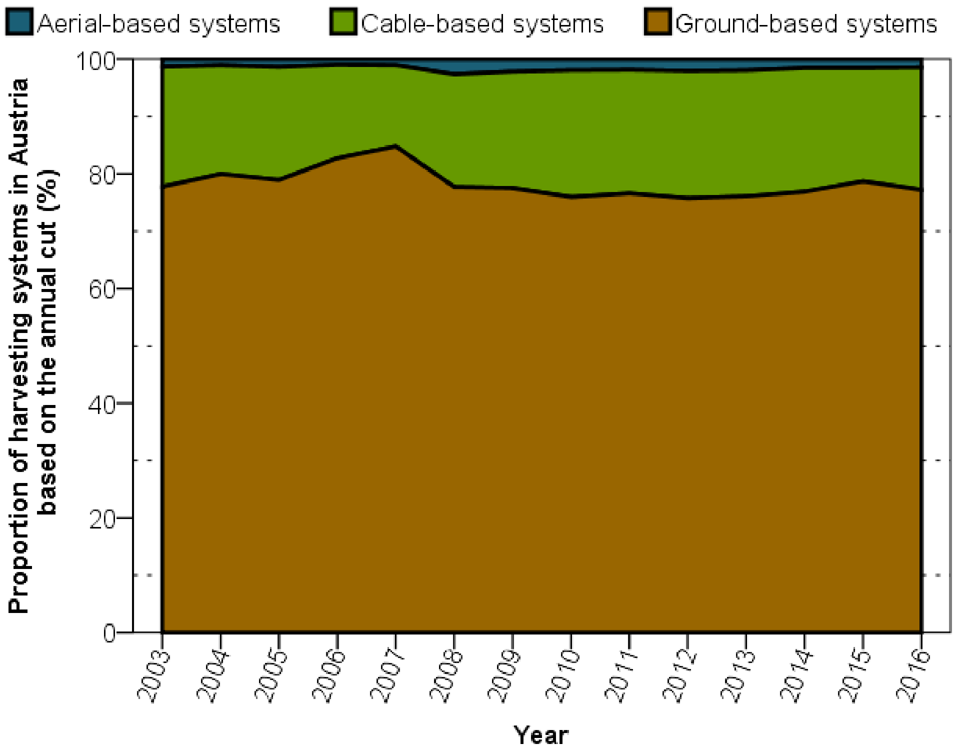

Figure 1: Proportion of the harvesting systems used in Austria during the last 14 years (BMLFUW, 2017).

Today, WT-cable yarding represents the state of the art harvesting method in steep terrain harvesting in Austria. At the Austrian State Forests, approximately 95% of the yarded timber is extracted by using WTH (ÖBf 2017, personal communication). CTL-cable yarding plays only a minor role and is mostly used for steep terrain harvesting at very sensible sites, like protection forests or in water protection zones (Lepkowicz 1998).

2.2 CTL and WTH – Strengths and weaknesses

A harvesting system has to fulfill several criteria, which all have to be met in order to remain successful in competition. Besides economical aspects, possible negative consequences and risks also have to be considered for comparing different harvesting alternatives. These considerations have to include both the assessment of working safety and possible ecological impacts.

2.2.1 Economic aspects

As already described in chapter 1.1, WTH did become the state of the art harvesting method in cable yarding mainly due to lower harvesting costs. System comparison in thinning operations carried out by Dürrstein and Stampfer (2000) clearly showed that the use of motor-manual WTH results in approximately 40% less harvesting costs than motor-manual CTL harvesting (Figure 2). According to their study, CTL-cable yarding is only economically competitive after fully mechanized felling and processing. However, although the gradeability of harvesters increased during the past years due to the employment traction aid winches, the use of mechanized CTL systems is still often limited by the presence of insurmountable obstacles.

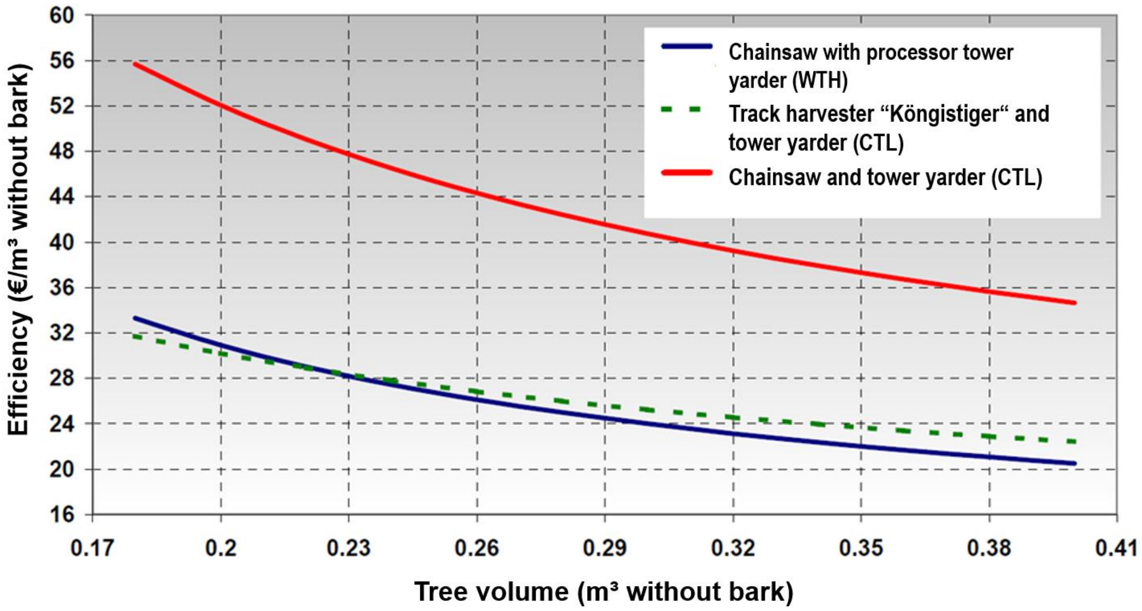

Figure 2: Comparison of system costs of thinning operations in steep terrain harvesting (Stampfer 2002)

2.2.2 Human stress and strain

The advancing mechanization of harvesting systems led to a significant reduction of physical labor. Modern cabins not only protect the machine operators from objects falling onto the machine (FOPS) or injuries caused by vehicle overturns or rollovers (ROPS), they also largely protect them from vibrations, noise, and weather conditions (heat, coldness, wetness, etc.). However, timber extraction with cable yarders requires at least one person, who is working in the stand and attaches logs to the mainline. This job is physically very demanding and often requires job rotation in order not to exceed the 40% cardiovascular load mark, which is defined as the limit of a sustainable work load for an eight hour working day (Stampfer 1996).

In motor-manual cable yarding, trees are felled (in CTL also delimbed and bucked) by a chainsaw operator. In WTH, this job can be carried out either by a separate worker or the choker setter, whereas in CTL harvesting usually at least two people – a choker-setter and a chainsaw operator – are working in the stand.

In addition to physical strain, chainsaw operators are also exposed to noise. Ear protector caps, integrated into the safety helmets, help them to protect their ears from harmful noise by reducing the sound pressure level below the exposure limit of 85 dB(A). In contrast to chainsaw operators, tower yarder operators are exposed to less noise. Modern cabins are able to reduce the sound pressure below 70 dB(A) (Pedarnig 2001) so that additional noise protection devices are not necessary.

Vibrations present another serious health hazard for chainsaw operators. In this context, hand-arm vibrations are of particular importance. Rottensteiner et al. (2012) showed, that hand-arm vibration values often exceed the worker's daily hand-arm vibration exposure limit A(8) of 5.0 m s^{-2}. As a consequence, measures like job rotation or job enlargement are of great importance for chainsaw operators in order to reduce vibration induced diseases.

Despite noise and vibrations, chainsaw operators are also exposed to exhaust gases. Nowadays, the use of special fuels is highly recommended and is able to significantly reduce the amount of CO_2 emissions and the exposure to carcinogens (Altzinger 2001). During the last ten years, the development of battery chainsaws, which do not emit any exhaust gases, has been strongly promoted. However, battery chainsaws are rarely used in professional harvesting operations, mainly due to their limited battery capacity and low engine power.

2.2.3 Ecological aspects

Residual stand damages

Especially after thinning operations, residual stand damages play a crucial role, because the subsequent infection with wood destroying fungi can lead to rot, which is able to impair the vitality and quality of infected trees (Butin 2002). However, a wound serves as a possible entrance point for pathogens and does not necessarily entail a loss in vitality and quality. Wound characteristics, like the intensity and size of a wound largely influence the speed of wound closure and thus the timeframe for possible infections (Vasilauskas 2001).

Kühmaier et al. (2016) demonstrated that the intensity and level of cable yarding damages to residual trees largely depends on factors like yarding direction, harvesting method, stand age, harvesting intensity, and slope conditions. They found that WTH caused significantly more damages to residual trees than motor-manual CTL harvesting. This finding is in good accordance with a former study, carried out by Limbeck-Lilienau (2003), who recorded twice as much damages after WTH than after CTL harvesting.

One of the main reasons for the increased number of stand damages in WTH is the fact that long pieces (i.e. whole trees) have to be swung into the cable corridor. Felling the trees in the fall line often help to reduce the proportion of damages. The use of so called “rub trees”, which are left next to the cable corridor, and the felling of trees in the fall line are often used measures which help to reduce the amount of tree damages. Cross-slope yarding, where partial suspended trees tend to slide downhill uncontrolled during extraction, is another reason for the high frequency of damages in WTH.

Another drawback of WTH is the fact that this harvesting method is only of very limited use for downhill yarding. Both during the lateral inhaul of the trees and during the inhaul of the carriage, the movement of the load can only be controlled to a very limited extent, causing considerable damage to the remaining stand. As a result, WTH is only used seldom for downhill yarding in thinning operations (Limbeck-Lilienau 2003).

Biomass and nutrient extraction

In CTL harvesting, trees are felled, delimbed, and bucked inside the stand. During yarding, only stem wood and bark gets extracted to the roadside. In contrast, delimbing and bucking is carried out outside the stand during WT-cable yarding, resulting in removing more biomass and nutrients from the forest site.

The primary nutrient's (nitrogen, phosphorus, and potassium) highest concentrations are found in foliage, while their lowest concentrations are found in stem wood. An Austrian study of aboveground biomass in a 48 year old Norway spruce stand showed that stem wood accounts for approximately 70% of the aboveground biomass while comprising less than 20% of total nutrient content (Lick, 1989). Needles contained 40% of the total aboveground nitrogen content while comprising less than 10% of total aboveground biomass.

Nitrogen is the nutrient mainly limiting growth in Austria. According to the Austrian Monitoring Program, nitrogen deficiency occurs at ca. 45% of the monitoring plots (Figure 3). Sufficient nitrogen supply has only been detected at ca. 13% of the inventory plots. Based on these findings, Englisch and Reiter (2009) calculated nutrient budgets for the different inventory points and came to the conclusion that WTH should not be used on 24% of the inventory points. As a consequence, there is a strong need to reduce the negative impacts of WTH on site productivity.

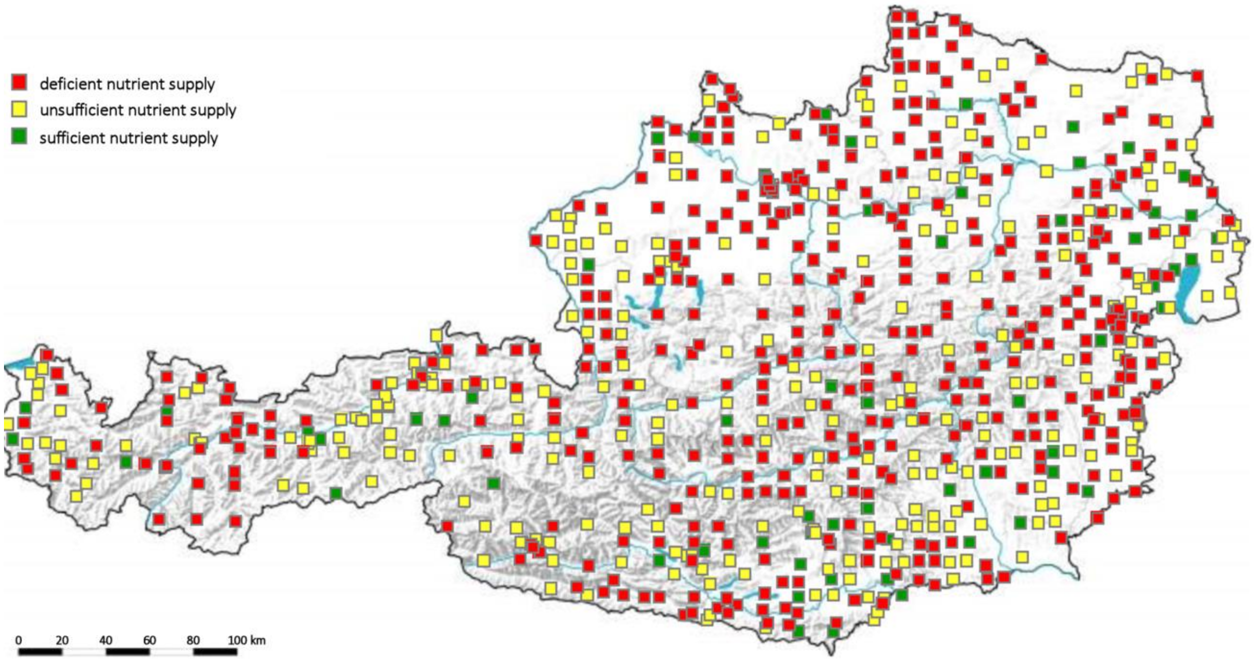

Figure 3: Nitrogen supply of Austria's forest in 2015 (BFW, 2017)

3

Methodological approach

. Publications I and II focus on the ecological and economic impacts of implementing topping strategies in WTH, while publication III and IV deal with the screening of chipped logging residues and the subsequent application of the fine screening rejects to harvesting sites. All four publications cover different research questions, which were answered by a set of different methods (Figure 4).

Evaluation of economic impacts

Time study analyzes were carried out within three publications (publications II, III, and IV) in order to determine the productivity of the studied systems. In publication II and IV, the recorded time study data served as a data basis for the development of productivity models. In publication III, time study data was used along with machine cost calculations to estimate the total screening costs per unit of output.

Evaluation of ecological impacts

In the first publication, biomass models were created in order to predict the effect of topping trees at various diameters on biomass removal in WT-cable yarding. The resulting biomass removal estimates were associated with nitrogen concentration values in order to allow estimates on nitrogen removal.

In publication III and IV, samples were taken from the different screening products (fine, medium, and coarse fraction). The samples were analyzed for particle-size distribution, ash content, energy content, nutrient concentration, and compartment composition in order to (1) assess the quality improvement through the screening of woodchips (Publication III) and (2) the suitability of the screening rejects for spreading with a modified centrifugal spreader (Publication IV).

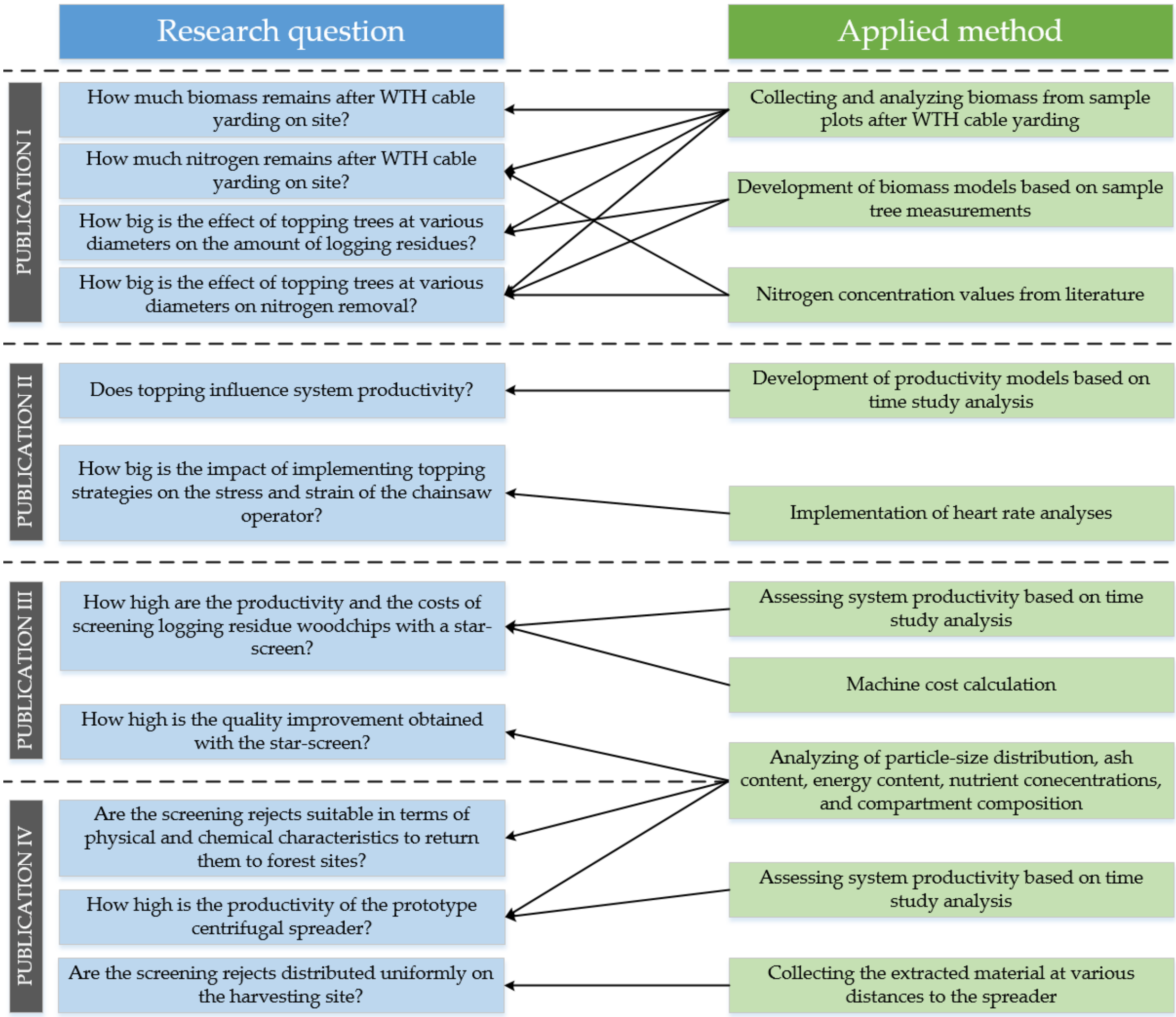

Figure 4: Overview of applied methods to investigate the research questions.

4

Summarized results

4.1 Paper I: Effect of topping trees on biomass and nitrogen removal in the thinning of Norway spruce stands

In this paper, the effect of topping trees at various stem diameters was assessed in order to estimate the amount of logging residues based on tree biomass models.

The results show that more than 60% of the total nitrogen of all felled trees remains on site after TL and CTL harvesting, where the whole crown biomass is left in the stand. In contrast, only 5 to 18% of the total nitrogen of all felled trees remains on site after conventional WTH without any topping activities. Removal of nutrients from the forest site after WTH was highest at first thinning stands and lowest at the second thinning stand.

The implementation of topping activities in WTH significantly reduced the removal of nutrients from the forest site. However, the choice of the topping diameter largely influenced the effect of topping trees on biomass on nutrient removal. The results show that the amount of nitrogen remaining on site progressively increases with increasing topping diameter. At all three study sites, topping trees at a diameter of 8 cm in WTH increases the amount of remaining nitrogen up to more than 30% of the total nitrogen of all felled trees.

Topping trees seems to be most efficient in young stands with high stand density. There the large number of felled trees directly leads to a big amount of tree top material, remaining on the forest floor.

4.2 Paper II: Efficiency of topping trees in cable yarding operations

Topping trees manually with a chainsaw not only increases the amount of biomass and nutrients that are left behind in the stand. Moreover, it influences the harvesting system as topping represents a new working task within the working cycle. The aim of this paper, which is strongly related to paper I, is to estimate the impact of topping strategies both on system productivity and on the stress and strain of the worker responsible for this additional working task. Three different treatments had been analyzed: (1) no topping is performed (reference treatment); (2) topping of downed trees; (3) topping of already hooked-on, lifted trees. The first treatment represents conventional WT-cable yarding (without topping trees) and serves as a reference. The 2nd treatment represents the standard topping treatment, where the trees are topped as soon as the tree hit the ground. The 3rd treatment is usually used for topping hang-ups or trees, whose crowns are not easily accessible to the worker.

The results show that topping of downed trees does not influence yarding productivity if harvesting is performed using a three men crew. There is enough time for the worker to fell and top trees without slowing down the productivity of the cable yarder. However, topping of hooked-on, lifted trees causes an interruption of the extraction cycles, which reduces system productivity between 5 and 11%. However the topping of trees represents an additional work task for the chainsaw operator and consequently increases his workload. Topping trees accounted for between 5 to 9% of his entire working time.

4.3 Paper III: Performance of a mobile star screen to improve woodchip quality

The aim of this paper was to analyze a mobile star screen, which was used to separate woodchips from logging residue piles into three size fractions in order to (1) increase woodchip quality and to (2) separate fine, nutrient-rich particles (mostly needles and fine branches). While the mid-size particles, which should mainly consist of nutrient-poor wood particles, are appropriate for heat or energy production, the nutrient-rich, fine particles should be used as a long-term fertilizer for forest application. Three different screen settings were analyzed, which are characterized by different rotation speeds of the stars of the fine screen deck. Both the unscreened woodchips and the different screened fractions were run for particle size distribution, calorific value, ash content, compartment and elemental composition.

Productivity of the star screen was 20.6 tons per productive system hour including delays up to 15 min. (PSH_{15}), corresponding to screening costs of on average 9.02 € per ton of unscreened woodchips. Screening of logging residue woodchips had a noticeable influence on material characteristics like particle size distribution, compartment and elemental composition, but did not significantly influence the calorific value. However, the study clearly showed that the screen setting largely influences screening quality. The highest quality of the screened material was achieved by the setting with the lowest rotation speed of the fine stars. However, a reduction of the rotation speed also increased screening costs per unit of screened material. For all screen settings, nutrient concentration of the rejected fine fraction was more than twice as high as of the unscreened material, indicating that it is possible to separate nutrient-rich particles by using a star screen.

4.4 Paper IV: Evaluation of a modified centrifugal spreader to apply nutrient-rich fine fractions from woodchips as a fertilizer to cutover areas in steep terrain

This study aimed to analyze a modified centrifugal spreader, which was used to spread fine rejects from woodchip screening on steep terrain cutover areas. The performance of the spreader was evaluated based on distribution uniformity and productivity. Several modifications of the centrifugal spreader were necessary in advance of the study. The spreader was equipped with a radio controlled engine unit and supporting arms, which were necessary to attach the spreader to the mainline of the cable yarder.

The results showed that the productivity of the spreader largely depended on the moisture content of the spread material. Moist material tended to decrease spreading productivity as it tended to lump and bridge inside the hopper. The spreader reached its highest productivity rate at a moisture content of 32%, ranging between 0.39 and 0.51 dry tons per productive system hour (PSH_0). Observed spreading distance was ca. 7 m to either side of the center of the spreader. The distance between the spreader and the ground did not influence the spreading width significantly. However, the spreader needs some adaption before it can be effectively used with screened fine woodchip particles. Improvements should focus on increasing spreading productivity and enlarging spreading width.

5

Discussion and Outlook

5.1 Topping trees

The results of this thesis show that topping trees in WT-cable yarding is an economical practicable method because it lowers the productivity of the yarding system only marginally and just leads to a slight increase of the harvesting costs. The results of publication I clearly show that topping trees is able to significantly increase the amount of nutrients remaining in the stand up to 300% in first thinning operations (assuming a topping diameter of 8 cm). However, the effect of topping trees on nutrient extraction seems to strongly rely on the number of harvested trees and consequently decreases with the ongoing developmental stage of a stand. The results of publication I already showed a substantially lower effect of topping trees on nutrient extraction after the second thinning operation than after first thinning operations. It is very likely that the effect of topping strategies further declines in subsequent harvesting operations. Further investigations need to be carried out to quantify the effect of topping strategies in final felling operations.

Nevertheless, besides the positive effect of topping trees on a stand's nutrient budget, some factors are able to limit the scope of topping trees:

The remaining tree tops on the harvesting sites may act as a habitat for insects. Especially large tree tops are of high risk to get infested by harmful bark beetles and may increase the risk of bark beetle attacks. Possible strategies to limit their reproduction rate are (1) to cut large tree tops into small pieces or (2) to reduce the topping diameter. Further studies need to investigate the effectiveness of this strategies.

During harvesting, tree tops may serve as obstacles for forest workers and obstruct ground visibility. As a consequence, they will affect the ease with which the workers can safely move over the harvesting site. In addition, remaining tops after final felling operations may also affect subsequent planting activities.

5.2 Screening of logging residues and returning screening rejects to forest sites

At present, there is an increasing demand of renewable sources due to the energy targets of the European Union, who aims to increase the proportion of renewables to represent 20% of the overall energy supply by 2020 (EU, 2009). As a consequence, there are still attempts to increase the energetic use of materials like logging residues, which, so far, are only used seldom for energy protection due to their poor quality. Especially logging residues from WT-cable yarding operations seem to have a high economic potential as they are already piled and easily accessible next to the forest roads.

The results of publication III show that it is possible to increase the quality of fresh logging residue woodchips in terms of particle size, and ash content. However, analyses showed that 20 to 40% of the needles are not detected as fine particles because they are attached to branches. In order to further increase screening quality, further studies should focus on the screening of drier logging residues.

The use of a star screen to separate small and oversize particles from logging residue woodchips turned out to be beneficial in terms of screening costs compared to screening devices used in other studies (Spinelli et al. 2011, Nati et al. 2015). Besides screening on intermediate storage places, screening can also be performed on forest roads or at heating plants. However, only little is known about the implementation of the screening process into woodchip supply chains.

The results of publication IV show that it is able to spread screening rejects over harvesting sites by using the tested modified centrifugal spreader. The material is spread out continuously onto the harvesting site up to a horizontal distance of approximately 7 m. However, the productivity of the spreader strongly depended on the moisture content of the screening material. Especially moist material (>35% moisture content) resulted in a low spreading productivity and can thus be not recommended for spreading. Further improvements of the spreader, like the use of a more powerful engine or the enlargement of the hopper-size, are highly recommended to enable an economic use of the machine in the future.

Transporting the material from the screening place to the harvesting site may act as a major logistic challenge, which has not been analyzed within the study. During the study, almost small big-bags (<2 m^3) were used to fill the hopper of the spreader. Due to the low concentration of nutrients of the spreading material of less than 1%, dozens of big-bags are necessary to compensate nutrient extraction from WT-cable yarding. However, the delivery of the big-bags to the spreading sites may be challenging due to the small storage place area on the forest roads, which is limited by the boom-reach of the tower yarder.

6

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Article

Effect of Topping Trees on Biomass and Nitrogen Removal in the Thinning of Norway Spruce Stands

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Abstract: In Central Europe, full-tree (FT) harvesting is an increasingly common harvesting method in steep terrain harvesting due to the increased use of highly economical processor tower yarders. In conventional FT harvesting, nutrient removal from harvest sites is substantially higher than in cut-to-length (CTL) harvesting due to the extraction of nutrient-rich branches and foliage. One strategy to reduce the adverse impact of FT harvesting is to cut off the tops of felled trees prior to extraction (topping). The purpose of this study was to assess the effect of implementing topping treatments in FT harvesting on biomass and nutrient removal. The effect of conventional FT harvesting on the amount of logging residues left on the site was assessed in three different Norway spruce (*Picea abies*)-dominated stands following cable yarding operations by collecting logging residues from the forest floor. The additional effect of topping trees on the amount of logging residues was assessed by using biomass models. These models were created based on the data of 25 sample trees, which were felled and sampled destructively within the stands. The results show that conventional FT harvesting considerably increases nutrient removal in comparison to CTL, but still do not remove all nutrients from the sites. After conventional FT harvesting, 5–18% of the nutrients remained on the sites. Topping trees at a diameter of 8 cm substantially increased the amount of remaining nutrients to 30–34%.

Keywords: FT harvesting; whole tree harvesting; nutrient removal; topping; cable yarding; biomass models; *Picea abies*

1. Introduction

In Central Europe, full-tree (FT) harvesting, which involves the removal of most of the nutrient-rich components of a tree from the harvesting site, has become more common in steep terrain harvesting. The main reason for the popularity of FT cable yarding is the development of so-called "processor tower yarders" in the late 1970s, which are equipped with boom-mounted processors. The use of these yarders resulted in cost-savings of about 40% for FT harvesting [1]. Today, processor tower yarders working with FT harvesting represent the state-of-the-art technology in steep terrain harvesting [1] and have largely replaced motor-manual cut-to-length (CTL) systems, where trees are delimbed and crosscut with chainsaws within the forest stands.

Another reason for the increased use of FT harvesting was the steadily growing interest in producing bioenergy from renewable resources [2]. In FT cable yarding operations, whole trees are extracted from the stand to the forest road. After processing the trees, branches and tree-tops are stacked in piles. Close to the forest road, these piles are easily accessible for follow-up machines, like chippers or grinders. As a result, the procurement costs of this material for further use is reduced because material collection and piling in the field is not necessary.

However, with the development and increased use of FT harvesting in the 1960s and 1970s, many researchers have already raised concerns over long-term site productivity effects of FT harvesting [3,4]. Since then, numerous studies on effects of FT harvesting, relative to those of CTL and tree-length (TL) harvesting methods, have been established. In particular, there have been numerous reports about the effect of different harvesting methods and treatments on tree growth (e.g., [5–7]). The majority of these studies concluded that FT harvesting can result in growth losses after thinning operations [5,6,8], and also negatively impacts seedling growth after regeneration felling [9]. In most of the studies it was assumed that nutrient removal from the forest site was the main reason for growth reduction [5,6].

Nevertheless, there is still uncertainty about the magnitude and durability of the effects of FT harvesting [10] since there are no available results on site productivity over multiple rotation periods. Consequently, some studies assessed the sustainability of forest sites based on nutrient balance calculations [11,12]. Nutrient budgets are calculated as the difference between inputs (e.g., deposition, weathering) and outputs (e.g., leaching, harvesting) over a specified time span. As such, nutrient balance calculations can be used as a means to identify nutrient depletion before it actually occurs. Thus, nutrient budgets can act as a useful basis to support forest decision-making processes [13]. However, conclusions from studies evaluating FT harvesting effects on nutrient budgets often assume that FT harvesting leads to a complete removal of all logging residues from the forest site [5,14], which results in a systematic overestimation of biomass and nutrient removal and unnecessarily exacerbates negative perceptions about FT harvesting. Several studies have already shown that it is not possible to remove all biomass from a site during harvesting operations [15–18]. Branches, foliage, and sometimes even parts of the stem break off during the different steps of harvesting operations: Firstly, branches break off during the falling of a cut tree since its branches are interlocked with branches of neighboring trees. Secondly, branch breakage occurs at the time when the tree hits the ground. Finally, tree parts break off during extraction when the trees are extracted to the landing.

Briedis et al. [15] found that 15% of the entire harvested material (45% of energy wood) remained on site after FT harvesting using a feller buncher and grapple skidder. Kizha and Han [18] found similar amounts of logging residues after a ground based and a cable yarded FT operation in California (U.S.), where 30% and 40% of the forest residues remained on site, respectively. Studies of Hytönen and Moilanan [16] have recently shown similar results in the thinning of Scots pine in Finland, where 32–66% of the harvest-generated residue material remained on site. However, the amount of biomass that remains on sites after harvesting operations may vary greatly from site to site, since the quantity of biomass removal depends not only on the harvesting method, but also to a decisive extent on factors like harvesting system, developmental stage of the stand, harvesting season, and tree species [14].

Nevertheless, at some sites, the amount of logging residues in FT harvesting might not be enough to ensure sustainability. Thus, there is a significant need for harvesting methods that increase the amount of logging residues in the forest in the most economical matter. One way to achieve this aim when using FT harvesting is to cut-off the tree-tops of felled trees within the stand before extraction. This procedure is commonly known as "topping". Tree-tops of conifers mainly consist of needles and fine branches, which contain a high proportion of a tree's nutrients [19–21] and are, thus, particularly important to a site's fertility. For instance, nutrient analysis of Kreutzer [4] on Norway spruce trees demonstrated that nitrogen concentrations of branches and needles are 12–21 times higher than of wood fibers. In accordance, nutrient models of Krapfenbauer [22] of a 100-year-old Norway spruce stand demonstrated that approx. 70% of the nitrogen is located in the crown biomass (branches and needles) of the trees.

Detailed nutrient analyses of Lick [20] further showed that needles in the upper part of the tree crown generally contain 15–20% higher nutrient concentrations than needles in the lower part of the crown. Considering this, topping trees seems to be an effective way to decrease the amount of nutrient removal during harvesting operations, since the tops of the trees contain the highest nutrient concentrations [20]. Nevertheless, topping trees represents an additional work task for the chainsaw operator and may also slightly decrease the productivity of the yarding system [23].

There are few studies on the amount of logging residues produced by using FT cable yarding. Little is known about the effect of topping trees at different topping diameters on the remaining biomass at different developmental stages of Norway spruce dominated stands. The objective of this study was to examine the impacts of different topping diameters both (i) on the amount of logging residues and (ii) the amount of nutrients, with a focus on nitrogen, remaining on the forest sites in first and second thinning stands after cable yarding.

2. Materials and Methods

2.1. Study Area

The study area is located in Central Austria, approximately 120 km southwest of Vienna (48°11′ N, 16°22′ E) and 30 km north of Graz (47°04′ N, 15°26′ E). This region is characterized by a subcontinental climate with a mean annual precipitation of 870 mm and a mean annual temperature of 7.9 °C. Average minimum temperatures in January range from −7 °C to 0 °C and average maximum temperatures in July range from 12 °C to 24 °C. The dominant soil type is brown soil. Humus form is mull and the thickness of the forest litter layer at the study sites varied between 1 cm and 3 cm, indicating medium turnover rates and moderate accumulation of nutrients.

2.2. Stand Characteristics

The study was carried out in three Norway spruce (*Picea abies*)-dominated stands (Table 1). All three stands are located close to one another (within a radius of 1 km) and are part of the same forest district. The stands differed from each other both by their age and pre-treatment:

Stand 1 represents a 58-year-old stand that had been thinned commercially at an age of 32 years. There was a strong need for a second thinning in order to increase stand stability and quality. The other two stands are much younger and were in need to be thinned commercially for the first time. In contrast to stand 3, stand 2 had been pre-commercially thinned in the thicket life stage.

Table 1. Site, stand, and harvesting characteristics of the study sites.

Parameter		Study Sites (Stands)		
		1	2	3
Harvesting operation		Second thinning	First thinning	First thinning
Previous operation		First thinning	Pre-commercial thinning	-
Harvesting area (m^2)		10,200	11,700	6800
Number of cable lines		2	2	2
Yarding distance (m)		170	250	125
Extraction direction		uphill	uphill	uphill
Stand age (years)		58	38	34
Average slope (%)		53	61	70
Species composition		85% spruce 9% larch 6% others	83% spruce 9% larch 8% others	80% spruce 10% birch 10% others
Stand density [1] (trees ha^{-1})	Before harvesting After harvesting	728 320	979 454	1667 500
Basal area [1] (m^2 ha^{-1})	Before harvesting After harvesting	52.4 31.9	26.4 15.7	34.2 17.1
Stand volume [1] (m^3 ha^{-1})	Before harvesting After harvesting	727 451	271 163	204 109

[1] DBH threshold: 6 cm.

2.3. *Estimation of Logging Residues after Conventional FT-Cable Yarding*

2.3.1. Harvesting Operations

At all three sites, FT cable yarding operations were performed by the same crew using a truck-mounted "Wanderfalke" tower yarder, extracting partially-suspended whole trees uphill to the forest road. No job rotation was practiced during the study time. The trees were felled motor-manually by a worker equipped with a chainsaw. The faller always started working at the lowest part of the stand and continued working uphill. Almost all trees were felled downhill, directional to the cable corridor in order to facilitate the extraction of trees and to reduce stand damage on residual trees. A second worker connected several trees to single loads, which were attached to the mainline and extracted uphill to the forest road by a slack-pulling carriage. At the roadside, a boom-mounted processor head delimbed and bucked the trees.

2.3.2. Estimation of Logging Residues

The estimation of the amount of logging residues was carried out directly after each yarding operation. The amount of logging residues left on the sites was assessed by collecting and weighing the material from 4 m^2 sample plots (2 m $\times$ 2 m), which were selected systematically (Figure 1): The plots were positioned every 40 m along the axis of the cable line; one plot located in the center of the cable corridor and two located laterally on each side of the corridor. Material, which extended beyond the edges of the sample plots, were cut at the border. The sample plots beneath the cable line represent the area of the cable corridor, assuming a corridor width of 3 m. The sample plots on the surrounding harvesting area represent the harvested area between the cable corridors, assuming a lateral yarding width of 15 m. In total, 24, 33, and 15 plots were located in the stands 1, 2, and 3, respectively. At each plot, live branches and needles were collected by hand and weighed in the forest stands using small big-bags (ca. 0.20 m^3) attached to a digital hanging scale with an accuracy of 0.1 g.

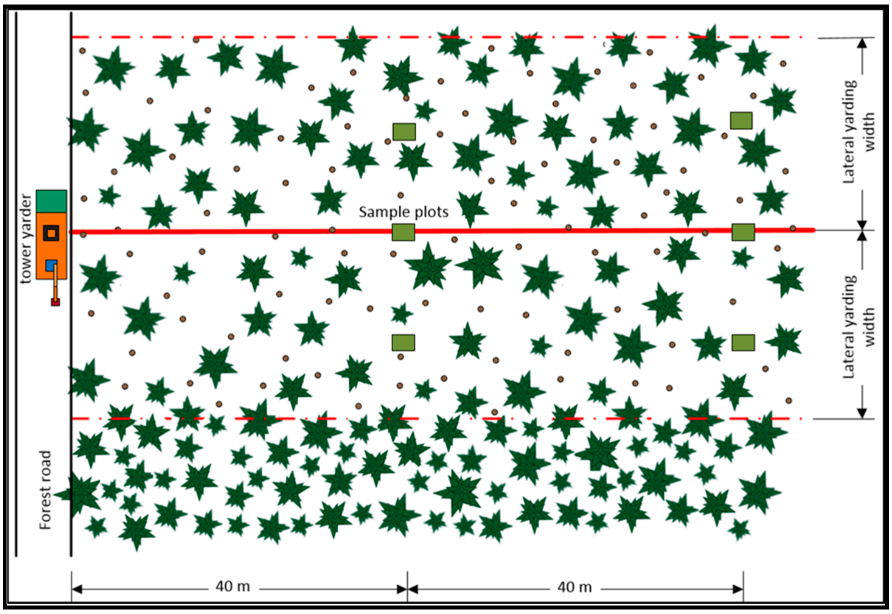

Figure 1. Estimation of logging residues after conventional FT cable yarding. Sample plots were positioned systematically across the harvesting area.

During the study time, there was hardly any understory vegetation due to the high stand densities prior the harvesting operations, which facilitated the identification of fresh, green needles and branches. Nevertheless, although collecting needles and live branches was somewhat easy, it was impossible to differ between dead branches of shortly felled trees and branches that were present prior the harvesting operation. Hence, we used data from literature [20] to estimate the biomass of dead branches, which broke during felling and extraction.

After weighing the logging residues of a plot, sub-samples were collected randomly to determine moisture content, the proportion of needles and the extent of contamination with stones or soil. Contamination was determined by using screening (particles smaller than 0.5 mm were regarded as soil) and sedimentation analyses (fast-sinking particles were regarded as stones).

2.4. Estimation of Total-Tree and Tree-Top Biomass

2.4.1. Stand Inventory

Prior to the harvesting operations, all trees of each study site were recorded according to DBH (diameter at 1.30 m above ground) and tree species. The associated tree and crown heights were measured randomly using a sample of at least 20 heights per stand in order to calculate species and site-specific height curves.

2.4.2. Felled-Tree Sampling

Across all diameter classes, eight to nine trees per stand, which were intended to be removed within the thinning operation, were chosen as sample trees (Table 2). Once the trees were felled, their basal diameter, DBH, total height and height to crown base were measured. Afterwards, each sample tree was cross-cut at the crown base and at stem diameters of 14, 8, 7, 6, and 4 cm (measured without bark). The mass of the components (stem wood, dead branches, live branches) were measured separately for each section using a big-bag attached to a digital hanging scale accurate to 0.1 g. Additionally, one live and one dead branch from the middle of each section were selected for laboratory analysis according to the following procedure: at each section, the length of all branches were measured. The branch, whose length was closest to the average length of the branches of a certain section, was chosen as a sample branch.

Table 2. Attributes of the felled Norway spruce sample trees.

Attribute	Mean	SD [1]	Min	Max
Stand 1—Second Thinning (*n* = 8)				
DBH (cm)	29.9	8.7	16.0	41.9
height (m)	29.1	3.8	22.1	34.1
crown length (m)	13.8	1.9	10.3	16.7
crown ratio (%)	47	4	39	54
Stand 2—First Thinning (*n* = 8)				
DBH (cm)	17.4	4.5	10.4	23.0
height (m)	18.3	3.0	12.4	20.8
crown length (m)	9.2	2.4	6.3	12.7
crown ratio (%)	50	8	36	61
Stand 3—First Thinning (*n* = 9)				
DBH (cm)	16.5	4.8	9.1	22.4
height (m)	16.5	4.3	7.1	21.0
crown length (m)	7.8	2.6	2.5	10.3
crown ratio (%)	46	8	35	62

[1] SD = standard deviation.

In total, a maximum of six of each, live and dead branches were selected per tree. Furthermore, stem disks were taken from the stem base and at stem diameters of 7 cm and 3 cm (measured without bark), which were subsequently divided into bark and debarked stem wood. The total moisture content of all samples (live branches, dead branches, bark, stem wood) was determined by drying them in an oven at 105 °C according to EN14774-2 (2009). During drying, most of the needles dropped off the live branches, which facilitated separating the needles from the branches afterwards. Ratios between fresh weight and dry weight of the samples were used to estimate their moisture content (MC) according to following Equation (1):

$$MC\ (\%) = 100 \times (m_1 - m_2)/m_1 \quad (1)$$

where m_1 is the mass of the sample before drying and m_2 is the mass of the sample after drying.

2.4.3. Tree Biomass Equations

Linear mixed effects models (LMMs) were used to estimate the aboveground biomass of each tree component (needles, live branches, dead branches, bark, and wood). Model forms for estimating tree-level biomass components contained tree DBH, total height (H), crown ratio (CR), and the relative basal area of larger trees (relBAL) as predictor variables. The variable "stand" was used as a random effect. The CR was calculated by dividing the live crown length of a tree by the total tree height. The BAL of a given subject tree is the sum of the basal area of all trees which are larger in DBH than the subject tree. To compare the social rank of trees of different stands, the relative basal area of larger trees (relBAL) was calculated for each tree (Equation (2)):

$$relBAL_{h,j} = BAL_{h,j}/BA_j \quad (2)$$

where $relBAL_{hj}$ is the relative basal area of larger trees of tree h in stand j; BAL_{hj} is the basal area of all trees larger than tree h in stand j; and BA_j is the total basal area of stand j.

In order to homogenize the variance of residuals, a log-linear equation was used (Equation (3)):

$$\ln(B_{i,j}) = \beta_0 + \beta_1 \ln(DBH_i) + \beta_2 \ln(H_i) + \beta_3 \ln(CR_i) + \beta_4 \ln(relBAL_i) + \mu_j + \varepsilon_{i,j} \quad (3)$$

where B_{ij} is the total biomass of component i in stand j, DBH, H, CR, and relBAL are covariates, $\beta_{0\ldots4}$ are model parameters, μ is an independent and identically distributed random variate that corresponds to between-stand variation, and ε is an error term.

For the estimation of the biomass of each component, a three-step process was used to select the best fit model [24]:

First, we determined the optimal structure of random effects by using restricted maximum likelihood estimation (REML) to fit several LMM's, which included all main effect terms for the covariates. Different specifications of the random effect were tested (random intercept only, random slope only, random intercept, and random slope). Akaike's information criterion (AIC) was used to identify the best fitting model. The LMM with the lowest AIC or the model with the fewest parameters, when AIC values of the lowest AIC model differed by less than two AIC units, was chosen. As a second step, we defined the ideal structure of the covariates by creating models with different combinations of covariates by using the random effect structure defined in the first step. Maximum likelihood estimation was used to fit the different models. As in step 1, AIC was used to identify the best fit model. As a last step, we fit a final model using REML for the model with the selected random effect structure of step 1 and the covariate structure defined in step 2.

Heteroscedasticity of the residual variances was checked for each model using explorative data analysis. If variance heteroscedasticity of a certain model was assumed, residual variances were modelled as a function of DBH, using several variance functions in R (varFixed, varExp, varPower, varConstPower). The effects of the variance functions were evaluated using AIC.

To predict the biomass of all trees within the stands, the model was transformed back to the original scale, which imposes a prediction bias. Consequently, a correction factor (cf) was used to compensate the downwards bias emerging from transformation:

$$cf_i = \Sigma B_{i(predicted)} / \Sigma B_{i(observed)} \quad (4)$$

where $B_{i(predicted)}$ are the back-transformed biomass values for component i using Equation (3) and $B_{i(observed)}$ are the measured biomass values of component i of the sample trees.

The statistical analyses were conducted using the nlme package [25] in R version 3.3.2 [26].

2.4.4. Tree-Top Biomass Equations

The same statistical procedure as described in Section 2.4.3 was used to determine the final model for estimating the biomass of tree-tops at different topping diameters (TD). Following general form was used:

$$\ln(B_{i,j,k}) = \beta_0 + \beta_1 \ln(DBH_i) + \beta_2 \ln(H_i) + \beta_3 \ln(CR_i) + \beta_4 \ln(relBAL) + \beta_5 \ln(TD_i) + \mu_j + \varepsilon_{i,j,k} \quad (5)$$

where B_{ijk} is the total biomass of component i in stand j at a topping diameter of k cm; DBH, H, CR, relBAL, and TD are covariates, $\beta_{0\,\ldots\,4}$ are model parameters, u is an independent and identically distributed random variate that corresponds to between-stand variation and ε is an error term.

Equation (5) was used to estimate the biomass of tree-tops for the components bark, wood, needles, and live branches. It was not used to calculate dead branches, due to their rare presence within the tree-tops.

2.5. Estimation of Biomass and Nitrogen Removal

If tree topping strategies are implemented in FT cable yarding, the remaining biomass consists of both:

- branches and foliage, which break off during felling and extraction (Section 2.3);
- biomass of tree-tops, which remain after topping the trees at a certain diameter (Section 2.4).

Nitrogen concentrations published by Lick [20] were used to estimate the impact of different topping scenarios on nitrogen removal. Nitrogen removal by using CTL harvesting has been calculated by using Equation (3), assuming that only bark and wood fibers are extracted to the forest road and all other compartments (needles, live and dead branches) remain in the stand.

3. Results

3.1. Logging Residues after Conventional FT Cable Yarding

After conventional FT harvesting, 2300 kg ha^{-1} to 8400 kg ha^{-1} of biomass (8–28% of the crown biomass of all felled trees) remained at the study sites (Figure 2). The amount of logging residues was much higher at the second thinning stand (stand 1; 8407 kg ha^{-1}) than at the two first thinning stands.

Especially at the second thinning stand, tree breakage—which mainly occurred when the felled trees hit the ground—turned out to be an important factor, which considerably increased the amount of logging residues from 4626 kg ha^{-1} up to 8397 kg ha^{-1}. Approximately 42% of the tree-tops broke off during the harvesting operation at an average diameter of 9.8 ± 3.7 cm. In contrast, tree breakage occurred less frequently at the first thinning stands. Only 1.6% and 16.6% of the trees broke at stands 2 and 3 at an average stem diameter of 5.0 ± 1.8 cm and 6.5 ± 3.3 cm, respectively.

At the first thinning stands, small, non-merchantable trees and bushes, which were felled to facilitate reaching the trees selected for removal, were left behind to keep system productivity high. Especially at stand 3, a large number of small trees (227 trees with an average DBH of 8.1 cm) was left behind at the forest site, which led to a significant increase of the remaining biomass from 949 kg ha^{-1} to 3450 kg ha^{-1}.

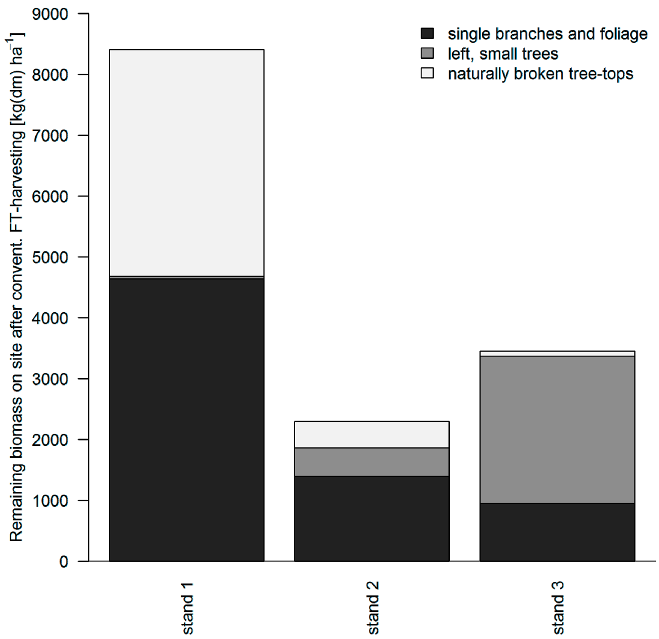

Figure 2. Amounts of logging residues at the experimental sites after conventional FT harvesting.

3.2. Distribution of Logging Residues after Conventional FT Cable Yarding

The accumulation of logging residues was highest in the vicinity of the extraction corridors (Figure 3). Especially in the first thinning stands, a significantly higher amount of logging residues was located on the extraction corridor than on the harvesting area (unpaired *t*-test, $p < 0.001$). In contrast, the remaining biomass was more evenly distributed at the second thinning stand due to a larger amount of logging residues at the harvesting area. At this site, no significant differences in biomass distribution could be found (unpaired *t*-test, $p = 0.099$).

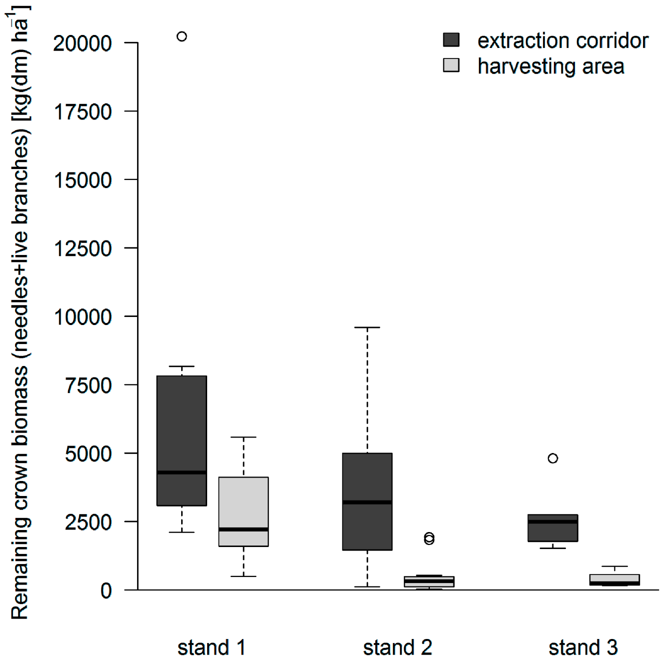

Figure 3. Lateral distribution of the remaining needle and twig biomass at the experimental sites.

3.3. Additional Effect of Topping on the Amount of Logging Residues

3.3.1. Tree Biomass Models

The final models for estimating the amount of component biomass of a tree are presented in Table 3. All parameter estimates of the aboveground tree component biomass models were statistically significant ($p < 0.05$) except the β_0 parameter estimate of the dead branch model. In general, the absolute amount of biomass for each component increased with greater DBH and tree height. Crown ratio (CR) explained a significant amount of variation only in the needle and dead branch models. The models show that the amount of needles significantly increases with greater CR, while the amount of dead branches decreases with greater CR. The differences between measured and back-transformed modelled biomasses turned out to be small.

Table 3. Estimated parameters of selected log-transformed aboveground tree component biomass models (Equation (3)), including model quality values (RMSE, AIC) and the bias correction factor (cf) (Equation (4)).

Component	*n*	**Parameter Estimates**					**RMSE**	**AIC**	**cf**
		β_0	β_1	β_2	β_3	β_4			
ln(Needles)	25	-9.748^{c}	2.507^{c}	-	1.219^{b}	-	0.244	22.2	1.007
ln(Live branches)	25	-5.059^{c}	2.613^{c}	-	-	-	0.308	28.5	1.026
ln(Dead branches)	25	1.645	2.539^{c}	-	-1.961^{b}	-	0.386	45.2	1.059
ln(Bark)	25	-5.054^{c}	1.719^{c}	0.795^{a}	-	-	0.160	1.5	1.015
ln(Wood)	25	-4.131^{c}	1.885^{c}	1.018^{c}	-	-	0.137	−8.4	0.976

[a] significant at $p < 0.05$; [b] significant at $p < 0.01$; [c] significant at $p < 0.001$.

3.3.2. Tree-Top Biomass Models

The biomass of tree-tops at different topping diameters was calculated to be able to estimate the effect of different topping strategies (i.e., topping diameter) on biomass removal.

AIC values of the models ranged from 92.5 to 164.4 and RMSE values ranged from 34% to 40% (Table 4). In general, the biomass of the tree-tops of each component increased with increasing topping diameter and tree height. Models, which included factors that describe the social rank of a tree (CR, BAL), showed a small predictive power (selection was based on AIC) and were, thus, not selected as final models.

Table 4. Estimated parameters of selected log-transformed tree-top biomass models (Equation (5)), including model quality values (RMSE, AIC) and the bias correction factor (cf) (Equation (4)).

Component	*n*	**Parameter estimates**						**RMSE**	**AIC**	**cf**
		β_0	β_1	β_2	β_3	β_4	β_5			
ln(Needles)	125	-7.324^{c}	-	1.553^{c}	-	-	1.906^{c}	0.402	164.4	1.037
ln(Live branches)	125	-6.031^{c}	0.942^{c}	-	-	-	2.223^{c}	0.399	152.7	1.089
ln(Bark)	125	-7.565^{c}	-0.914^{c}	0.996^{b}	-	-	3.247^{c}	0.399	126.4	0.928
ln(Wood)	125	-6.427^{c}	-1.213^{c}	1.141^{c}	-	-	3.669^{c}	0.336	92.5	0.936

[a] significant at $p < 0.05$; [b] significant at $p < 0.01$; [c] significant at $p < 0.001$.

3.4. Scenario Analyses

After the first thinning operations (stands 2 and 3), only 3–8% of the biomass remained at the forest sites as logging residues (Figure 4) after conventional FT cable yarding. The implementation of topping strategies substantially increased the amount of logging residues and, thus, reduced the extraction of nitrogen from the forest sites. Topping the trees at a diameter of 4 cm resulted in an increase of logging residues by 43–67%. The use of a topping diameter of 8 cm would even increase the amount of logging resides by 260–370%, resulting in a total amount of logging residues between 14% and 18%.

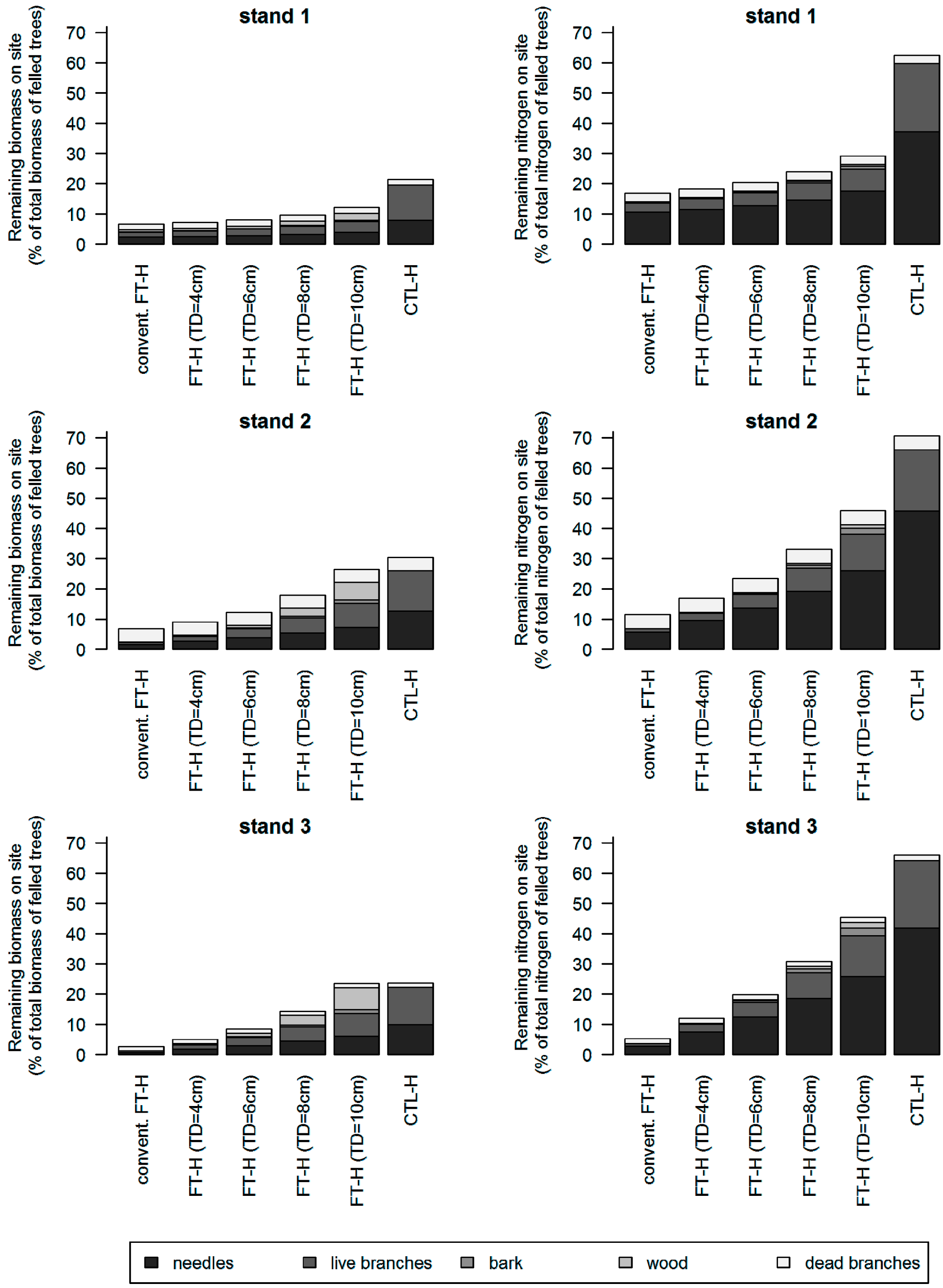

Figure 4. Relative biomass (% of total tree biomass of extracted trees, **left column**) and relative nitrogen (% of total nitrogen within the biomass of extracted trees, **right column**) at the three study sites under different management scenarios: conventional FT-H (FT harvesting without topping), FT-H (4 cm) (FT harvesting and topping of all trees at 4 cm), FT-H (6 cm) (FT harvesting and topping of all trees at 6 cm), FT-H (8 cm) (FT harvesting and topping of all trees at 8 cm), FT-H (10 cm) (FT harvesting and topping of all trees at 10 cm), and CTL-H (Cut-to-length harvesting, where all branches and needles remain on site).

After the second thinning operation (stand 1), 7% of the biomass remained on the site after conventional FT harvesting. In contrast to the first thinning operations (stands 2 and 3), the implementation of topping strategies resulted in a slight increase of the logging residues. Topping trees at a diameter of 8 cm only increases the amount of logging residues by 40%.

However, topping of trees mainly increases the amount of nutrient-rich needles and live branches within the logging residues. Other compartments, like wood and dead branches are not affected that much. As a result, an increase in the topping diameter (within the studied range up to a topping diameter of 10 cm) leads to a progressive, strong increase of the amount of nitrogen remaining on the sites. Topping trees at 8 cm within first thinning operations limits the amount of nitrogen extraction to ca. 65%. By using this topping diameter, almost half the amount of logging residues, which would remain in the stand after CTL-harvesting, were left behind in the stands.

4. Discussion

The purpose of this study was to analyze the effect of different topping strategies on the amount of logging residues and remaining nitrogen after FT cable yarding operations. The results clearly indicate that FT harvesting considerably increases nitrogen removal in comparison to CTL-harvesting systems, but still does not remove all nutrients from sites. Furthermore, the results showed that—especially in first thinning operations—topping is an effective way to decrease nitrogen losses due to harvesting.

The results of the present study show large differences in nitrogen removal between the study sites during conventional FT harvesting. Factors such as tree breakage or the leaving of non-merchantable trees in the stand played decisive roles at the study sites, which both substantially increased the amount of logging residues. The findings of this study correspond with those of Hytönen and Moilanen [16], who examined the amount of logging residues in 40–80 year old pine stands in Central Finland using ground-based harvesting machines, although they found somewhat higher amounts of logging residues after conventional FT harvesting, ranging from 32–66% of that of CTL-harvesting. Nevertheless, it has to be taken into account, that differences in factors like tree species, terrain, harvesting period, and harvesting systems may influence branch breakage and, thus, the amount of logging residues to a decisive extent.

According to the results of our study, the implementation of topping in FT cable yarding seems to be a promising strategy to decrease the negative ecological impacts of FT harvesting. Time studies already showed that the productivity of the cable yarding system decreases only marginally if topping of trees is performed [23]. Other studies on strategies, which aim to increase the nutrient pool of forest sites, including airborne fertilizer applications [27,28] and the spreading of wood ash [29,30], showed much higher costs.

The results of this study clearly show that the effect of topping trees on both the amount of logging residues and the amount of remaining nitrogen is highest in first thinning operations, which are usually characterized by a high stand density and a high number of trees that need to be harvested. This result is not surprising, since the number of remaining tree-tops and, thus, the effect of topping trees at a certain diameter is directly linked with the number of harvested trees. As a consequence, the positive ecological impact of topping trees increases with the number of harvested trees. In consideration of these findings, the results of these studies demonstrate that the implementation of topping strategies is especially advantageous in early thinning operations.

However, the decision whether to top trees or not, as well as the choice of the topping diameter, is a difficult and often-studied topic for many forest companies. One relevant driver in forest management decisions, which limits the implementation of topping strategies, is the increased risk of fatal insect outbreaks. Insect species, like the European spruce bark beetle (*Ips typographus*), or the six-toothed spruce bark beetle (*Pityogenes chalcographus*) are one of the major biotic disturbances in Central European Norway spruce stands [31]. Especially, *Pityogenes chalcographus* is of particular interest because this beetle, in contrast to *Ips typographus*, prefers to attack small diameter wood, like tree-tops [32]. However, the hazard of bark beetle attacks can be reduced both, by cutting the tree-tops to smaller pieces in order to increase drying speed or by avoiding harvesting operations during spring and summer at sites with high risk of bark beetle attacks.

However, one of the main limitation of this study is that it was not possible to distinguish between pre-existing dead branches and dead branches, which broke off during the harvesting operation. An additional pre-harvest forest residue sampling may serve as one opportunity for further study to assess the amount of logging residues with higher accuracy.

5. Conclusions

The results of this study show that topping trees is an effective way to minimize the export of nitrogen from forest sites when using FT cable yarding. In first thinning operations, only 5–12% of the nitrogen remained at the forest sites. The implementation of topping strategies substantially increases the amount of logging residues and reduces the amount of nitrogen extraction from the forest sites, and the topping diameter substantially increased the amount of logging residues. The effect of topping trees in second thinning operations was somewhat lower. However, the effect of topping largely depends on the topping diameter. Up to a topping diameter of 10 cm, the additional amount of nitrogen remaining on the sites increases nearly exponentially with increasing topping diameter.

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Publication II

Efficiency of topping trees in cable yarding operations.

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Efficiency of Topping Trees in Cable Yarding Operations

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Abstract

The extraction of biomass and nutrients out of the forest is implicit to every harvest operation. In cable yarding, whole-tree harvesting (WTH) has become more prevalent in the last few decades and processing takes place at the roadside. There is a concern that WTH impairs site productivity due to nutrient removal. One option to increase the amount of biomass remaining in the stand is to top the trees before extraction. In order to estimate the influence of topping on system productivity, time studies on a medium-sized tower yarder were carried out in three spruce dominated stands. Heart rate monitoring of the chainsaw operator was performed to examine the physiological workload. The analysis showed that topping only impacts system productivity if it takes place during the inhaul of the load as it leads to interruptions of the extraction progress. These interruptions took on average 13 seconds per turn. In addition, if topping was performed on already lifted trees, a reduction of line-speed during the lateral yarding of the loads was observed. This led to a reduction in productivity between 5 and 11%, assuming that all trees would have been topped during the lateral yarding process. Analyses of the physical workload of the chainsaw operator showed that the workload of topping trees is significantly lower than that of the felling process. Relative heart rate of the subject was lower at the cable corridors where topping was ordered. This confounding result may be a consequence of many additional factors like slope gradient or cycle time. Under both scenarios, the worker never surpassed the limit of a sustainable cardio-vascular workload for an 8 hour working day. Hence, recovery time for the chainsaw operator can be considered as adequate when topping is performed in a three-man crew.

Keywords: topping, cable yarding, productivity, workload

1. Introduction

Efficient harvesting in steep terrain is usually linked to cable based harvesting systems. The use of whole-tree harvesting (WTH) has become more common in Central Europe, mainly due to the technological development of boom-mounted processors. Heinimann et al. (2001) estimated that the use of a processor in cable logging results in cost savings of about 40% compared to motor-manual cut-to-length (CTL) systems.

The change from CTL to WTH leads to a shift of the delimbing process from within the forest to the roadside. This results in a greater removal of biomass and nutrients from the forest stand. The increased removal of the nutrient richest parts of the trees (needles and twigs) has raised concerns about the sustainability of WTH (e.g. Raulund-Rasmussen et al. 2008, Kaarakka et al. 2013, Tveite and Hanssen 2013).

One method to increase the amount of logging residues, remaining in the forest when using WTH, is to top the trees. Nutrient analyses show that young needles contain higher concentrations of most nutrients than older needles, branches or stem wood (Lick 1989). Hence, topping trees is an effective way to increase the amount of nutrients left in the stand as tops contain predominantly young needles and twigs. The advantage of this treatment is dependent on the topping diameter. On the one hand, the quantity of branch and needle residue is largely affected by the topping diameter, but on the other hand the selection of the topping diameter can be influenced by changes in price and demand of wood. The topping diameter may also affect the length of the stem section, which may influence optimal bucking and consequently impair the grade, and thus the value, of the resulting logs.

Motor-manual topping of trees in the forest stand using a chainsaw may increase the workload of the chainsaw operator. It is also likely that topping lowers productivity of the harvesting system, depending on the integration of topping into the working process. However, studies on the economical and ergonomic effects of motor-manual topping in cable logging are lacking.

The purpose of this study was to examine the impact of topping on the productivity of a tower yarder operating in thinning operations of Norway spruce (*Picea abies*). The effect of topping on the workload of the chainsaw operator was also investigated.

2. Materials and methods

2.1 Study site

The thinning experiments were set up in early autumn 2014 in three Norway spruce (*Picea abies*) dominated stands in the eastern part of the Austrian Alps. The three stands differ from each other both by their age and silvicultural pre-treatment (Table 1). At the 34 year old study site »Bairhübl«, no prior thinning had been performed. As a consequence this stand is characterized by a high number of stems (1667 stems/ha) in comparison with the 38 year old study site »Bergtal« (979 stems/ha), which had been thinned once in the thicket-life stage. The third stand »Klommegger« represents a 58 year old stand that had been thinned once. All three stands were considered to be in need of thinning. The slope gradient of the three study sites ranged from 50 to 80%.

2.2 Experimental design

The thinning harvesting operation was performed using a truck-mounted »Wanderfalke« yarder, developed by the company »Mayr-Melnhof«, extracting whole trees uphill to the forest road. The tower yarder was equipped with a Mayr-Melnhof Sherpa U3.0 carriage with a maximum load capacity of 3 tons. At the roadside, processing was done using a Woody H50 processor developed by »Konrad Forsttechnik«. The tower yarder worked in a three-line gravity system, where the third cable (haulback line) is used to pull slack on the mainline.

The crew, consisting of one yarder operator, one choker setter and one chainsaw operator, was constant over the whole experimental period. No job rotation occurred between the workers. At the study site »Bairhübl«, the choker-setter was replaced by another one at the second cable corridor.

During the operation, the chainsaw operator felled a few trees (ca. 5–15) in advance so that the choker-

Table 1 Site and stand characteristics of experiments

Parameter	»Klommegger«		»Bergtal«		»Bairhübl«	
	Corridor 1	Corridor 2	Corridor 1	Corridor 2	Corridor 1	Corridor 2
Coordinates (position of the yarder at corridor 1)	47°19'33.1"N, 15°19'16.6"E 845 m		47°20'13.3"N, 15°20'51.9"E 628 m		47°19'11.1"N, 15°20'31.4"E 822 m	
Operation type	Second thinning		First thinning		First thinning	
Previous operation	First thinning		Cleaning		-	
Number of trees before operation, stems/ha	728		979		1667	
Number of trees after operation, stems/ha	320		454		500	
Average DBH before operation, cm	29.3		18.2		15.5	
Average DBH after operation, cm	35.0		20.5		20.0	
Treatment	Without topping	Topping	Without topping	Topping	Without topping	Topping
Length of cable corridor, m	170	170	240	255	110	140
Average inclination, %	54	51	60	62	68	71
Average piece volume, m^3	0.67	0.61	0.19	0.21	0.16	0.19
Average number of trees per load	1.69	1.69	2.15	2.12	2.63	2.44

setter was not hindered in his job. Another advantage of this working method is that it helps the choker-setter to make an optimum load because he is able to choose between different stems to hook on.

At each study site, two cable corridors were analyzed. At the first corridor, full trees including branches and tops were extracted uphill to the roadside. At the second corridor, all trees were topped by the chainsaw operator at a diameter of approximately 6 cm.

Topping was usually performed during the lateral yarding process before the trees were fully pulled up to the skyline (Fig. 1), which led to an interruption in the extraction progress. During this delay period, the chainsaw operator moved to the head of the trees and topped them. The extraction process continued when the worker was standing in a safe position. This procedure provides the only way to top hung-up trees in the forest stand, but was also applied to facilitate the work of the chainsaw operator. In some cases, at the convenience of the chainsaw operator, trees were topped before the chokers were set.

Fig. 1 Topping of an already lifted tree during lateral yarding process

Table 2 Work task definitions used in three time studies

Cable yarding system	
Outhaul	Carriage movement from the landing to the choker-setter
Hook-on	Starts when the rigging is lowered (carriage positioning is included) and ends when the load reaches the carriage
Inhaul	Carriage movement from the stand to the landing
Grounding the load	Time of lowering the rigging and positioning the load at the landing
Unhooking the load	Starts when the yarder-operator gets off his seat to detach the chain strops and ends when he takes a seat in the cab
Raise rigging at landing	Time to raise the rigging until it reaches the carriage
Waiting	Operational delay time
Choker-setter	
Lower rigging	Time to spool out the mainline until the worker grabs it
Hook-on	Required time to move to the trees, to attach strops to them and to retreat to a safe position afterwards
Break-out	Time to raise the load and pre-extract it to the cable line until it reaches the carriage
Waiting during topping	Time the working progress of the choker-setter is interrupted by topping trees
Waiting	Operational delay time within which the choker setter is both waiting for the carriage and planning the next load
Chainsaw operator	
Felling	Time to fell a tree (including the steps: select and assess trees, clear vegetation around the base, felling the tree, observe tree fall)
Topping	Time to move to the trees and to top them
Other PSH_0	Other activities like crosscutting or fueling the chainsaw
Waiting	Operational delay times within the chainsaw operator is hindered by the choker-setter
General work tasks used in all three studies	
Delays<15 min	Delays shorter than 15 minutes
Delays>15 min	Delays longer than 15 minutes

2.3 Time studies

In order to record process variables that may influence time or system productivity, all trees of each study site were recorded according to tree species and *DBH* (diameter at 130 cm height). The associated heights were measured randomly using a sample of at least 20 heights per tree species and stand. To allocate each felled tree to a specific extraction process, all trees were numbered consecutively using aerosol cans. To estimate the extraction distance of each load in the field, the distance to the landing was measured along the cable corridor and marked on some residual stand trees next to the corridor.

Time studies were performed to illustrate the effect of topping on system productivity. Data collections were carried out using three mobile tablet PCs »ALGIZ 7« running in a Windows 7® environment, using a continuous timing method. To analyze the time of each working process, the working cycle of each crew-member was split into several functional elements (Table 2). Parallel to the time consumption measurements, the number of each harvested tree, as well as the extraction distance, was noted during the observation of the choker setter.

2.4 Physiological measurements

The workload of the chainsaw operator was estimated based on heart rate measurements because direct measurement methods, such as the maximum oxygen uptake of a worker ($VO_{2\,max}$), are difficult to obtain under field conditions (Kirk and Sullman 2001). The heart rate of the subject was measured at 1 sec intervals for the entire working time using a Polar RS800 running computer. The computer consists of a heartbeat-capturing transmitting unit and a receiver-storage unit. Before data collection, the transmitter is attached to a strap and secured around the subject's chest just below the chest muscles. The transmitter sends the heart rate signal directly to the running computer, which displays and records the data. The use of sport heart rate monitors has already been proved successfully in several ergonomic studies (Vogelaere et al. 1986, Stampfer et al. 2010, Magagnotti and Spinelli 2012).

At the start of each working day, the heart rate monitor was attached to the chainsaw operator and started simultaneously with the time study software on the hand-held field computer »ALGIZ 7« in order to be able to merge the working heart rate (HR_w) data set with the time study data set. The resting heart rate (HR_r) was obtained for the subject upon arrival at the work site. Therefore, the chainsaw operator was asked to remain seated inside the car without moving, drinking or smoking for a minimum of 10 min. The minimum heart rate within this time period was selected as his resting heart rate. The maximum heart rate (HR_{max}) was estimated by using the standard formula (Rodahl 1989):

$$HR_{max} = 220 - Age \tag{1}$$

Relative heart rate at work (% *HRR*) was determined by applying the following equation (Rodahl 1989, Apud 1989):

$$\%\,HRR = \frac{HR_w - HR_r}{HR_{max} - HR_r} \cdot 100 \tag{2}$$

Where:

% *HRR* relative heart rate at work;
HR_w heart rate at work;
HR_r heart rate at rest;
HR_{max} maximum heart rate.

In total, 28 hours of chainsaw operator heart-rate data were collected. The pre-work resting heart rate of the 32 year old subject was 55 bt./min.

2.5 Statistical analysis

Height curves were computed for each stand using the *DBH* as independent variable, with *b* being the coefficient and *a* being the constant:

$$ln(h - 1.3) = a + b \times \frac{1}{DBH} \tag{3}$$

The height of each tree was predicted from the tree height calculated by the height curve, and the volume was calculated using the cubing formulas according to Pollanschütz (1974).

Former productivity studies on tower yarders (e.g. Stampfer 2002, Stampfer et al. 2010, Talbot et al. 2014) showed that the mean piece volumes, extraction distance and harvesting intensity are the main factors influencing system productivity. The following productivity hypothesis is used in this study:

Yarding productivity = f (mean volume per piece (tree vol), Extraction distance (dist), cutting intensity (int), Slope gradient (grad), topping)

As some of these variables only influence parts of the extraction cycle, the productivity of the harvesting system (m^3/PSH_{15}) was determined by calculating individual efficiency models of the main elements of the extraction cycle (cp. Nurminen 2006):

$$Prod_{yarder} = \frac{60}{c \times (eff_{hook\text{-}on} + eff_{carriage} + eff_{landing})} \tag{4}$$

Table 3 *Variables used to describe yarding productivity*

Factors	Topping	(0) Without topping; (1) With topping	2 levels
Covariates	Mean volume per piece	Mean tree volume per load	m^3
	Extraction distance	Distance between tower yarder and stopping position of the carriage	m
	Cutting intensity	Removed fraction of volume in a defined area during harvest operation	%
	Slope gradient	Slope steepness within a defined area	%

Table 3 gives an overview of the variables used to calculate the productivity of the harvesting system.

The hook-on phase involves all activities at the felling site, starting with lowering the rigging and ending with the completed lateral inhaul of the load, and the carriage phase comprises the inhaul and outhaul of the carriage. All working tasks at the landing, including grounding and unhooking the load as well as raising the rigging, are summarized in the landing phase. In order to include delays of up to 15 minutes in the model, a conversion factor (c) of 1.3 was used.

Analysis of variance was used to analyze the influence of co-variables and factors, including analysis of interactions between the variables (Stampfer 2002). Due to the nonlinear relationship between the average tree volume and efficiency, the co-variable »average tree volume per cycle« was transformed using power functions. The suitability of the exponents was evaluated by the coefficient of determination and the distribution of the residuals. In order to estimate the coefficients of the variables used in the models, regression analysis was made.

ANOVA techniques were used to check the statistical differences between the different study sites and treatments. All analyses were carried out using both Microsoft® Excel 2013 and PASW 18.0 for Windows.

3. Results

3.1 Productivity analysis

Interruptions of the working process, which occurred when trees were topped during the lateral inhaul of the load, took on average 12.65±6.68 seconds (Fig. 2) and were significantly higher (Tukey-HSD, p=0.0236) at the first thinning stand »Bairhübl« (14.11±7.49 sec) than at the second thinning stand »Klommegger« (11.05±5.95 sec). The expenditure of time for topping the trees at the study site »Bergtal« was on average 12.05±5.98 seconds and did not differ significantly from the other two stands.

The study also showed that breaking out a load takes more time when topping takes place during the lateral yarding process, even if the interruption times due to topping the trees are not included. This average prolongation of the break-out process, not including any interruption times during this phase, was greatest at »Bergtal« (23.79%), followed by »Klommegger« (15.74%) and »Bairhübl« (11.89%).

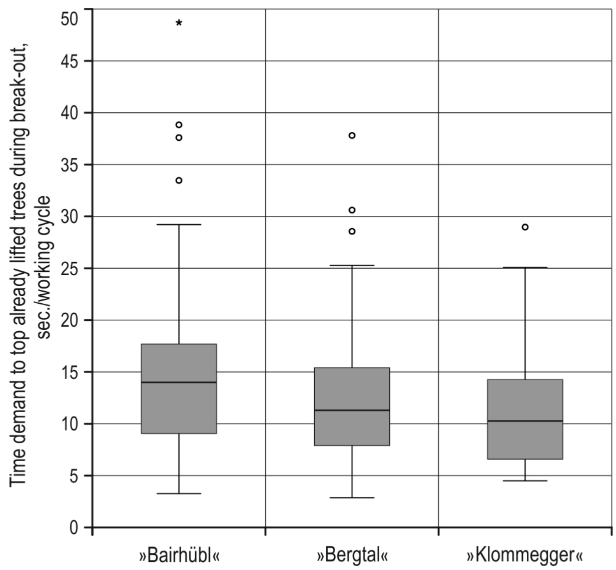

Fig. 2 Delay durations resulting from topping trees during the lateral yarding phase

Topping the trees during the lateral yarding process was mainly performed at the first thinning stands due to a high number of hang ups. Interruptions due to topping trees occurred in 69.17% (»Bairhübl«) and 65.99% (»Bergtal«) of the extraction cycles. In the other cases, the trees were topped before they were attached. In contrast to the first thinning stands, at the study site »Klommegger« only 44.44% of the loads were topped during the break-out task. This result is directly linked to a high number of broken stems during felling, which resulted in fewer trees that had to be topped. At »Klommegger«, 42.20% of the felled trees broke during the felling and extraction operation at an average diameter of 9.77±3.74 cm. At the other two sites, tree breakage occurred less frequently, being more frequent at »Bergtal« (16.60%) than at »Bairhübl« (1.55%). At these two stands, the average size of the broken pieces was 5.02±1.78 cm and 6.50±3.32 cm, respectively, for »Bergtal« and »Bairhübl«.

Based on the chronometry data of 692 cycles and inventory data, efficiency models (min/m^3) for the main elements of the extraction cycle were calculated:

$$eff_{\text{hook-on}} = \beta_1 \times tree\ volume^{-0.9} + \beta_2 \times inc + \beta_3 \times topping$$

$$[R^2_{\text{adj.}} = 0.87;\ F\ (3{,}689) = 1571.55,\ p<0.001] \quad (5)$$

$$eff_{\text{carriage}} = \beta_1 \times tree\ volume^{-0.9} + \beta_2 \times inc + \beta_3 \times dist$$

$$[R^2_{\text{adj.}} = 0.79;\ F\ (3{,}688) = 882.31,\ p<0{,}001] \quad (6)$$

$$eff_{\text{landing}} = \beta_1 \times tree\ volume^{-0.9}$$

$$[R^2_{\text{adj.}} = 0.77;\ F\ (1{,}689) = 2332.61,\ p<0{,}001] \quad (7)$$

Regression results for the efficiency models are reported in Table 4.

The average tree volume per load (tree volume) influenced significantly the efficiency of all three cycle elements. During both the hook-on phase and the carriage phase the slope gradient played a significant role. The equations show that a higher inclination (inc) influences the efficiency (min/m^3) of the hook-on phase in a positive way, and of the carriage phase in a negative way. Topping the trees during the extraction process (topping) only affects the efficiency of the hook-on phase, while the extraction distance (dist) had a significant influence on the efficiency of the carriage phase.

The overall mean values of the variables (Table 3) were used to calculate productivity models (Fig. 3) of the logging systems using treatments with and without topping the trees, as a function of the average tree volume. According to the productivity model, topping leads to a decrease of the average system productivity

Table 4 Regression model parameters for the extraction cycle elements

	Hook-on phase			Carriage phase			Landing phase
	$ß_1$	$ß_2$	$ß_3$	$ß_1$	$ß_2$	$ß_3$	$ß_1$
Coefficients	0.84	0.01	0.50	0.60	-0.01	0.01	0.38
Standard error	0.03	0.00	0.16	0.03	0.00	0.00	0.01
t-stat	27.01	4.48	3.21	21.28	-3.15	8.71	48.30
p-value	<.001	<.001	.001	<.001	.002	<.001	<.001

Table 5 Comparison of relative heart rate, *DBH* of felled trees and number of felled trees per minute within the felling task. Interruptions >15 min. are not included

Results for		Without topping trees	With topping trees	*p* value[a]
»Klommegger«	% *HRR*	26.71	23.43	<.001
	Av. *DBH* of felled trees	24.44	24.53	.895
	Felled trees/min. felling time	1.73	1.36	.001
»Bergtal«	% *HRR*	27.79	27.51	.001
	Av. *DBH* of felled trees	15.96	16.35	.308
	Felled trees/min. felling time	2.04	1.84	.119
»Bairhübl«	% *HRR*	35.26	31.91	<.001
	Av. *DBH* of felled trees	11.98	15.45	<.001
	Felled trees/min. felling time	4.52	2.57	<.001

[a] Statistical significance for the equality of treatment means

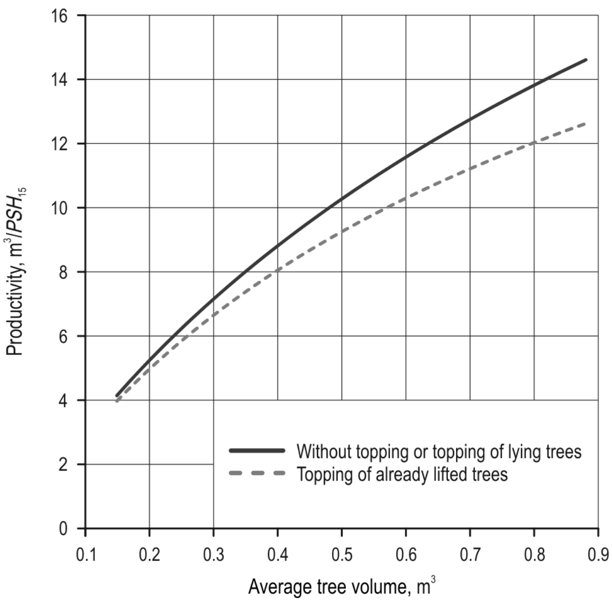

Fig. 3 Productivity of cable yarding system depending on tree volume and integration of topping into the working process

from 5.25 m^3/PSH_{15} to 4.97 m^3/PSH_{15} (-5.36%) and from 4.78 m^3/PSH_{15} to 4.54 m^3/PSH_{15} (-4.90%), respectively, for »Bergtal« and »Bairhübl«, assuming that all trees would have been topped during the lateral yarding phase. At »Klommegger«, topping all trees after attaching them to the mainline would reduce the productivity from 11.92 m^3/PSH_{15} to 10.56 m^3/PSH_{15} (-11.39%). However, productivity loss due to topping was much smaller because of tree breakage and numerous trees that had been topped before they got hooked on. Considering these factors, topping trees decreased system productivity in fact to 4.62 m^3/PSH_{15} (-3.39%), 5.06 m^3/PSH_{15} (-3.54%) and 11.32 m^3/PSH_{15} (-5.06%), respectively, at »Bairhübl«, »Bergtal« and »Klommegger«.

It is very likely that topping trees not only affects system productivity, which results in higher harvesting costs, but also increases the workload of the chainsaw operator. Hence, the time of each work phase was determined for the chainsaw operator (Fig. 4). The diagram illustrates that felling trees was the longest work task within the working cycle consuming 30 to 45% of the entire working time. At the cable corridors where topping was required, it took the chainsaw operator between 4.76% (»Klommegger«) and 8.59%

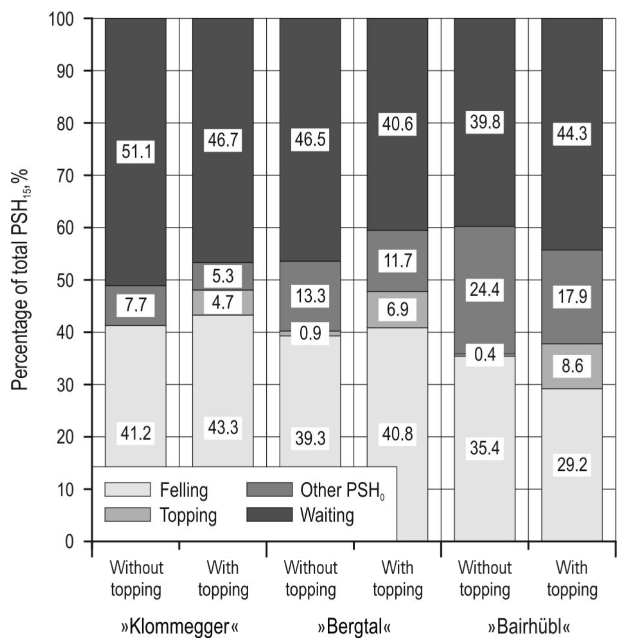

Fig. 4 Time consumption of different working tasks of the chainsaw operator

Table 6 Relative heart rate (%*HRR*) by working tasks at different study sites and treatments. Pairwise comparisons were performed, and different statistically significant means ($p<0.05$) were marked with different letters

Study site	Treatment	Felling	Topping	Other PSH_0	Operational delays	Delays >15 min	*F* value	*p* value[a]
»Klommegger«	With topping	23.55a	21.9b	22.47b	22.69b	22.57b	17.90	<.001
	Without topping	28.25a	-	27.99a	28.09a	18.94b	792.05	<.001
»Bergtal«	With topping	28.73a	27.24b	27.39b	27.54b	24.15c	166.52	<.001
	Without topping	29.83a	-	30.33a	27.33b	18.32c	929.44	<.001
»Bairhübl«	With topping	34.30a	31.11b	33.64c	31.57b	26.34d	423.38	<.001
	Without topping	37.32a	-	37.00ab	36.96b	31.04c	1802.07	<.001

[a] Statistical significance for the equality of treatment means

(»Bairhübl«) of his working time (PSH_{15}) to top trees. The working task »other PSH_0« was mainly scrub-cleaning and was most time consuming at the first thinning stands, especially at »Bairhübl«, where no previous silvicultural treatment had been performed.

3.2 Heart rate analysis

Table 5 shows the relative heart rate of the chainsaw operator in conjunction with the average *DBH* of the felled trees and the average number of felled trees per minute within the felling task. The results are presented separately for the three study sites. Overall, the relative heart rate of the chainsaw operator was significantly lower at all three sites at the cable corridors where topping was performed. At the study site »Bairhübl«, the average *DBH* of the felled trees differed significantly between the two treatments. During the felling task, a significantly higher number of trees were felled by the chainsaw operator at study sites »Bairhübl« and »Klommegger«. However, the average resting heart rate never surpassed the 40% cardiovascular load mark, which is defined as the limit of a sustainable workload for an 8 hour working day (Stampfer 1996).

Table 6 shows the differences in relative heart rate between different work tasks of the chainsaw operator. The highest physiological workloads were measured during the felling task. At 50% of the cable corridors, relative heart rate of the felling task was significantly higher than at any other working task. No significant differences were observed between the working tasks topping and operational delays. Both work steps were characterized by significantly lower relative heart rates compared to the felling task.

4. Discussion

Topping seems to decrease system productivity only when it is performed during the break-out phase because the lateral yarding process has to be delayed. These interruptions took on average 12.65 seconds, and were longer at the first thinning stands than at the second thinning stand »Klommegger«. It seems to be very likely that these differences in time demand are directly associated with the number of trees per load. While at the study sites »Bairhübl« and »Bergtal«, an average load consisted of 2.52±0.78 and 2.14±0.86 stems, respectively, at »Klommegger« only 1.69±0.70 stems formed a load. If a load consists of more trees, it will take more time to top all the trees. Conversely, the average time to top a single tree will probably decrease if the load is formed by a higher number of stems.

The results show that the break-out phase is not only prolonged because of interruption times due to topping the trees. Also the time to spool in the mainline in order to pull the load to the carriage, not including any interruptions, required more time at all sites when trees were topped during the lateral yarding phase. It is very likely that factors like positioning the load next to the chainsaw operator or reducing the line speed to minimize hazards for the chainsaw operator may decrease the extraction speed.

At »Klommegger«, tree breakage was an important factor influencing the quantity of trees that had to be topped. In comparison to the other two study sites, the size of the broken pieces was much larger at Klommegger. This observation concurs well with Fitec (2000), reporting that trees usually break at 2/3 of their total height.

Topping trees during the break-out phase not only affects productivity and logging costs; it also poses hazards for the chainsaw operator. Partially suspended trees can have tension and compression forces within them that make the job of topping more difficult and dangerous. Unexpected release of stems or unplanned load movement during topping may also be a significant safety hazard for the worker.

Additionally, topping trees also influences the time consumption of the chainsaw operator, mainly by the need to walk longer distances. A large amount of broken or topped trees remaining at the forest site also affects the ease with which the workers can safely move at the cutover area. However, Fig. 3 shows that the operational delay times of the chainsaw operator was at least 40%. During this period he was mainly waiting until most of the felled trees were extracted by the choker-setter. Consequently, a large part of this period can be considered as recovery time.

Table 5 showed that an introduction of topping trees into the working process of the chainsaw operator resulted in a statistically significant reduction of relative heart rate, although topping was included as an additional work task into his working process. It is very likely that the reduced workload relates to the chainsaw operator working at a lower pace when topping was ordered, but also other factors like slope gradient or walking distances may have influenced the physical workload and covered other effects.

5. Conclusions

Topping can be a useful treatment to increase the amount of logging residues remaining at the forest site. When working with a three-man crew, this study showed a decrease in system productivity by only 3.4 to 5.1%. Consequently, the harvesting costs increase by approximately 1.00–2.50 €/m^3. Topping does affect the work time of the chainsaw operator. Especially in steep terrain, walking to the head of the trees to top them can be a time-consuming task. However, in this study, physiological workload measurements of the chainsaw operator showed that the average heart rate reserve never surpassed the endurance limit of performance at any working task. Therefore, recovery time for the chainsaw operator can be considered as adequate when working in a three-man crew.

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Article

Performance of a Mobile Star Screen to Improve Woodchip Quality of Forest Residues

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Abstract: Low harvesting costs and increasing demand for forest-derived biomass led to an increased use of full-tree (FT) harvesting in steep terrain areas in Austria. Logging residues, as a by-product of FT harvesting, present an easily accessible bioenergy resource, but high portions of fine particles and contaminants like earth particles and stones make them a complex and difficult fuel, as they affect storage capability, conversion efficiency, or emission rates adversely. The present research focuses on the productivity and performance of a star screen, which was used to remove fine and oversize particles from previously chipped, fresh Norway spruce (*Picea abies* (L.) Karst.) logging residue woodchips. Three screen settings, which differed in terms of different rotation speeds of the fine star elements (1861 rpm, 2239 rpm, 2624 rpm) were analyzed. Time studies of the star screen were carried out to estimate screening productivity and costs. Furthermore, 115 samples were collected from all material streams, which were assessed for particle size distribution, calorific value, ash content, and component and elemental composition. Average productivity was 20.6 tonnes (t) per productive system hour (PSH_{15}), corresponding to screening costs of 9.02 €/t. The results indicated that the screening of chipped logging residues with a star screen influenced material characteristics of the medium fraction, as it decreased the ash content, the incidence of fine particles, and the nutrient content. The different screen settings had a noticeable influence on the quality characteristics of the screening products. An increase of the rotation speed of the fine stars reduced screening costs per unit of screened material in the medium fraction, but also lowered screening quality.

Keywords: screening; logging residue; woodchips; quality; cost; productivity

1. Introduction

About 47% of the Austrian land area is covered by forests [1], whereof 22% of the forest area is characterized by terrain slopes greater than 60% [2]. On such steep slopes, ground-based harvesting systems, even equipped with traction winches, often reach their physical and ecological limits [3]. Hence, cable-based harvesting systems, using tower yarders for extracting timber from the forest stand to the forest road, are still widely used in steep terrain harvesting. Common harvesting methods are cut-to-length (CTL), tree-length (TL), and full-tree (FT) harvesting. Until the 1990s, motor-manual CTL systems, where the trees are felled, delimbed, and bucked manually to assortments of varying lengths within the stand, were widely used in steep terrain harvesting. The development of processor heads with gripping capabilities in the early 1990s resulted in an increased use of FT harvesting systems, in which the trees are delimbed and bucked at the roadside. Heinimann et al. [4] estimated that the mechanization of tree processing results in cost savings of about 40%. Today, processor tower yarders working with FT harvesting represent the state-of-the-art technology in steep terrain harvesting in Central Europe.

However, the increased use of FT harvesting involves a greater removal of nutrients from the harvesting site, as the tree parts with the highest nutrient content, needles and twigs, are largely removed from the site. Consequently, several studies [5–8] dealing with possible impacts of FT harvesting on site productivity were conducted all around the world. The conclusions of the studies were somewhat different: several studies have found significant negative impacts of FT harvesting on site productivity [5,6], while another did not observe any negative impacts [8]. In general, it seems that the impact of FT harvesting on soil productivity mainly depends on the forest and soil type.

During FT cable yarding operations, branches and non-merchantable tops (logging residues) are piled next to the forest road. The current options for brush piles in Central Europe are either: (i) to leave them on site to decay or (ii) to use them for energy production. Analysis on changes of the nutrient distributions around remaining brush piles showed that nutrient release is limited to the vicinity of the remaining piles [9]. Given the fact that extraction distances in cable yarding operations are quite often longer than 200 m, the impact of remaining brush piles as a nutrient source for the entire forest stand can be ignored. Within the last few years, the utilization of brush piles gained importance due to the fact that political and social pressures are continually increasing the need for renewable energy sources. Nevertheless, the use of logging residues as an energy source still plays a minor role due to great variability in its product characteristics (particle size, ash content, moisture content, etc.) [10] and higher procurement costs compared to sawmill by-products [11]. Hence, to further promote the use of logging residues, it is necessary to both reduce procurement costs by optimizing supply chain management and to achieve higher selling prices by increasing product quality [11,12].

Green chips (woodchips made of fresh logging residues including branches and tops) are a very heterogeneous material, which make them a complex and difficult fuel due to their high variability in terms of material composition and characteristics. Their quality varies strongly according to tree, site, and stand characteristics, harvesting season, and silvicultural treatment [13]. Moreover, logging residue woodchips as a primary source of biomass fuel are characterized by irregular particle size and shape, high moisture content, low bulk density, and the presence of contaminants (earth, stones), which affect its storage capabilities and application possibilities [10]. Small and medium sized heating plants are especially sensitive to biomass fuels of different poor quality. In contrast to industrial users, they usually require woodchips with low moisture content and small particle lengths [14].

Particle size distribution is one of the most important woodchip characteristics influencing conversion efficiency and emission rates [15]. The removal of fine particles increases storage stability, as it favors air circulation inside the pile, which hampers spore formation and accelerates the drying process. On the other hand, the removal of oversize particles reduces the risk of bridging or arching, which is especially problematic in small heating plants, whose conveying ducts are relatively small and can be blocked easily by long particles [16].

Recently, some studies have examined methods that could improve wood biomass characteristics to meet the product quality required by heating plants. While some studies focused on different chipper or grinder settings [17–19], others dealt with different screening machines, which are used to improve the quality of woodchips [14,20–23]. Although all studies concluded that it is possible to significantly increase fuel quality by screening, screening before combustion is still only performed occasionally.

After screening, the medium sized particles are directly transported to an energy facility, while the coarse particles usually require further chipping before combustion. The fine particles can either be discharged in the forest or transported to a composting plant. Alternatively, a completely new approach would be to return the fine particles to some forest sites in order to reduce the ecological impact of utilizing logging residues for energy production by increasing the nutrient pool of some sites [24].

Studies on screening performance are infrequent and mainly focused on quality improvements of woodchips. Furthermore, little is known about nutrient and tree part composition of the rejected fines, which are crucial factors needed to evaluate the suitability of this material for composting or field application. The aim of this study was to analyze the performance of a star screen specifically designed to remove fine and coarse size particles in order to increase woodchip quality, operating with three different machine settings. In particular, the study aimed to determine: (i) the material properties of untreated chips from fresh cable yarding brush piles; (ii) the productivity and the cost of the screening process; (iii) the obtained quality improvement of the logging residue woodchips; and (iv) the suitability of separated fines in terms of physical and chemical characteristics to be either composted or returned to the forest site as a nutrient source.

2. Materials and Methods

A mobile drum chipper (Albach Silvator 2000) was used to comminute fresh logging residue piles (time since harvest was shorter than 20 days) after different FT cable yarding operations. The chipper was equipped with 12 chipping knives, which had been sharpened at the beginning of the chipping operation. All logging residues originated from pure Norway spruce (*Picea abies*) stands. In total, brush piles from 11 thinning and 12 clear-cut operations were used within this study. The chipper was equipped with 12 chipping knives and a 100-mm sieve. At the roadside, the chips were blown directly into container trucks, which transported the chips to a terminal station, where the chips were screened within the next three days.

A mobile star screen "Multistar L3", developed in Austria by the company "Komptech" (Figure 1), was used to separate fresh logging residue woodchips into three fractions (fine, medium, coarse). The machine was powered by a 60-kW diesel engine and was located at a bituminized terminal station. The main machine characteristics are presented in Table 1.

Figure 1. Mobile star screen "Multistar L3" fed by a wheeled front-end loader.

Table 1. Main machine characteristics of the star screen.

Manufacturer	Komptech GmbH
Model	Multistar L3
Year of manufacture	2009
Engine type	diesel generator
Engine power	60 kVA
Weight (transport position)	ca. 19 t
Dimensions in transport position (L × W × H)	11.3 × 2.6 × 4.0 m
Dimensions in working position (L × W × H)	12.8 × 6.3 × 4.0 m
Hopper volume	ca. 7 m^3
Coarse screen dimensions (L × W)	3.2 × 1.3 m
Fine screen dimensions (L × W)	5.8 × 1.3 m
Max. throughput capacity	180 m^3/h

Material was deposited onto the screen by a wheeled front-end loader, which poured the fresh woodchips inside the 7-m^3 hopper of the screen (Figure 2). Inside the hopper, a scraper floor continuously conveyed the material to a dosing roller, which distributed the woodchips consistently onto the coarse screen deck. This deck consists of many robust, rotating star-elements, which are arranged in multiple rows. The stars were made of rubber and feature a cleaning finger that clears the screening gap to the surrounding stars at each rotation in order to prevent material blockage. Oversize particles make it all the way to the end of the screening deck, whereas smaller particles fall through the spacings between the stars onto a conveyor belt, which delivers them to the fine star deck. In contrast to the coarse screen deck, the rubber stars of the fine deck are much smaller and more elastic. Commercial, medium sized woodchips make it all the way to the end of the fine screen deck, whereas fine particles fall through the spacings between the stars.

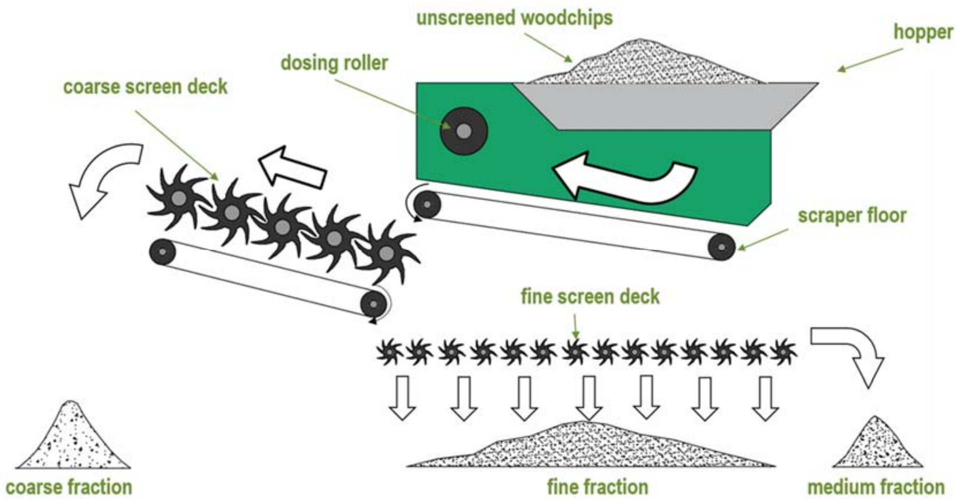

Figure 2. Simplified operating principle of a star screen.

Three different screen settings were analyzed within this study: The rotation speed of the hydraulic engine, which powers the stars at the fine screen deck, was set to either 1861 rpm (62% of maximum speed), 2239 rpm (74% of maximum speed), or 2624 rpm (87% of maximum speed), whereas all other screen settings (speeds of scraper floor, dosing roller, and stars of the coarse screen deck) were kept constant during the whole study time. The hydraulic engine, which powers the scraper floor and the dosing roller at the same time, was set to 880 rpm, and the rotation speed of the engine that powers the stars of the coarse screen deck was set to 2415 rpm. The different screen settings of the fine screen deck were selected based on recommendations of the manufacturer, the experience of the machine owners, and the results of test runs (optical inspection of screening products at different settings). The fresh logging residue woodchips, which derived from different harvesting operations, were assigned randomly to the three different settings of the fine screen deck. In total, six treatments (Table 2) were examined with variables including rotation speeds of the stars and harvest type (thinning, clear-cut).

Table 2. Treatment block.

Setting of the Fine Screen Deck	Harvest Type	Number of Harvesting Sites Sampled
1861 rpm (62% of Max. Speed)	Thinning Clear-cut	4 4
2239 rpm (74% of Max. Speed)	Thinning Clear-cut	3 4
2624 rpm (87% of Max. Speed)	Thinning Clear-cut	4 4

2.1. Product Analyses

At the terminal, woodchips of the 23 harvesting sites were piled separately to be able to distinguish between the different treatments. Four material streams were sampled at the beginning, at the middle, and at the end of each screening operation: the unscreened material, the fine fraction, the medium fraction, and the coarse fraction. At each screening operation, all three samples of the same material stream were combined to one composite sample to produce a representative sample of each material stream of a given woodchip pile. From each of these composite samples, a ca. 16-L sample was bagged, labeled, and immediately weighed on-site to determine the initial mass. Subsequently, the samples were oven dried in the laboratory at 105 °C to a constant mass. Dry masses were compared with the corresponding initial masses in order to estimate moisture content at a wet basis according to international standards [25]. The reported values within this study are an average of two measurements.

The dried samples were further analyzed for particle-size distribution [26], component composition, heating value [27], ash content [28], and elemental composition [29]. Therefore, each sample was separated into five sub-samples with different masses.

Mechanical particle size distribution was analyzed using a one-dimensional horizontal sieve shaker (GFL 3016). The sieve shaker was set to an amplitude of 30 mm and a frequency of 300 rpm. Seven classification sieves with square holes (Ø 400 mm) were used to determine particle-size distribution: 63 mm, 45 mm, 31.5 mm, 16 mm, 8 mm, 3.15 mm, and 1 mm. For simplicity, the different fractions were grouped into three functional classes: fines (<3.15 mm), acceptable (3.15 mm–63 mm), and oversize particles (>100 mm).

Component composition was determined on 100 g (fine fraction) to 1000 g (coarse fraction) sub-samples by sorting them manually into the following groups: fibers, bark, branches, needles, dust, and others (e.g., stones and other inorganic materials). Particles smaller than 0.75 mm were principally assigned to dust because it was impossible to assign them to a specific group without doubt.

Sub-samples of ca. 100 g were taken from each composite sample to determine the calorific value and the ash content. A "Retsch SM100" cutting mill, equipped with a 1-mm sieve, was used to comminute the sub-samples roughly. A "Retsch GM200" knife mill was further used to comminute the samples to a particle size of at least 1 mm. One gram of the samples was pressed to pellets with a "Parr manual press" before it was burned in an "IKA C200" bomb calorimeter. Another previously milled sub sample of ca. 3 g was used to determine the ash content according to international standards [28].

One-way ANOVA and samples t-tests were performed using the SPSS 21 statistical package (IBM Corp., Chicago, IL, USA) to determine significant differences between treatments. Statistical differences at an alpha level of 0.05 indicated product differences for a number of categories between treatments. The Bonferroni method was used to adjust *p*-values for multiple comparisons.

2.2. Production and Cost Analyses

Net weight of each loaded truck was recorded at delivery to the terminal station at a weigh-bridge. During screening, the fine and coarse fraction were directly discharged into containers (see Figure 1), which were also weighed at the terminal station directly after each screening cycle. The mass of the medium fraction was calculated by subtracting the net-mass of the fine and coarse fraction from the mass of the unscreened material.

The time study consisted of 23 woodchip piles, each consisting between 5.68 and 26.43 tonnes of green chips. Each pile originated from different FT cable yarding operations close to the city of Leoben, Styria in Austria (47°12′45.3″ N, 14°51′14.6″ E). The time study was carried out manually using a portable handheld computer (AlGiz 7, Handheld, Lidköping, Sweden). The working time was recorded at a cycle level by applying a continuous timing method. The observation unit was the screening of one whole chip pile. Overall working time of the star screen was divided into effective working time (PSH_0) and delay times. Effective working time was defined as the time span in which material was delivered from the hopper to the coarse screen deck.

The calculation of the machine costs was conducted with a few modifications according to the Scheme of Food and Agriculture Organization of the United Nations [30]. The following assumptions were made (Table 3): According to information from local dealers, the investment costs are ca. 350,000.00 € for the star screen and ca. 165,000.00 € for the wheel loader. The annual utilization rates for both the wheel loader and the star screen were set to 1000 PMH_{15} (productive machine hours per year, including delays up to 15 min) each. The annual interest costs were calculated at an interest rate of 5.0%. The depreciation period was assumed to be 10 years. Repair and maintenance costs for the star screen and the loader were estimated to be 26.25 €/PMH_{15} and 8.79 €/PMH_{15}, respectively. Fuel consumption of the machines was calculated using a fuel price of 1.20 €/L and the net power of the machines. The lubricants costs were assumed to be 25% of the fuel costs. To run the whole system, only one worker was required to operate the wheel loader. The labor costs including wages were set to 30 €/PMH_{15}. All calculations were made without sales tax.

Table 3. Cost assumptions and calculated machine costs.

	Star Screen (Multistar L3)	**Wheel Loader (Volvo L110H)**	**Unit**
Input Data			
Purchase price	350,000.00	165,000.00	€
Expected useful life	10,000	13,000	PMH_{15}
Technical obsolescence	10	10	Years
Annual utilization	1000	1000	PMH_{15}
Utilization barrier	1000	1300	PMH_{15}
Interest rate	5.0	5.0	%
Repair cost ratio	0.75	0.90	
Material Costs			
Interest	8.75	4.13	€/PMH_{15}
Insurance	3.40	3.80	€/PMH_{15}
Depreciation	35.00	16.50	€/PMH_{15}
Repair costs	26.25	8.79	€/PMH_{15}
Fuel costs	10.08	27.36	€/PMH_{15}
Lubricant costs	2.02	5.47	€/PMH_{15}
Total Material Costs	85.50	66.05	€/PMH_{15}
Labor Costs	0.00	30.00	€/PMH_{15}
Total Machine Costs	85.50	96.05	€/PMH_{15}
Total System Costs	181.55		€/PSH_{15}

Note: PMH_{15} = Productive Machine Hours, including delays up to 15 min; PSH_{15} = Productive System Hours, including delays up to 15 min.

3. Results

3.1. Productivity and Cost

Figure 3 shows the resulting amounts of the different material streams after screening. The mass fraction of screening rejects (fines and coarse fraction) varied in the range of 20.2% to 41.2%, depending on the screen settings. The results clearly show that a reduction in rotation speed of the fine stars leads to a significantly higher amount of screening rejects and lowers the amount of material in the medium fraction. However, a change of the rotation speed of the fine stars does not influence the amount of the rejected coarse fraction. The mass of the fine and the medium fraction all differed significantly from each other ($p < 0.050$) at the three different fine screen settings analyzed within this study.

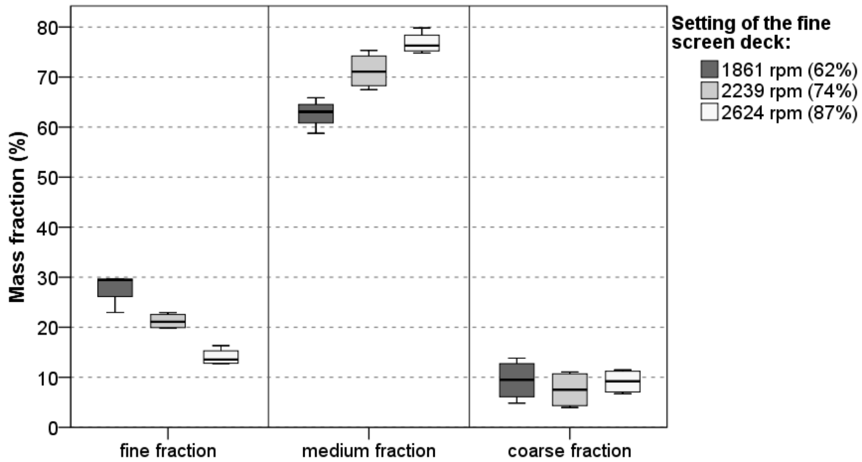

Figure 3. Mass fraction in percent after screening application for the tested fine screen settings.

The average gross productivity of the tested machines was 20.99 t/PSH$_0$ (Table 4). During the time study, few delay times were observed. Delay times of less than 15 min amounted to 1.02% of the total PSH$_{15}$. Almost all delay times were related to human caused operational errors, which occurred at the beginnings of the first screening cycles.

Table 4. Productivity and cost of screening logging residue woodchips. The presented results were calculated based on the amount of unscreened woodchips.

	Unit	Mean	SD
Moisture content	%	44.58	1.44
Productivity	t/PSH$_0$	20.99	2.75
	t/PSH$_{15}$	20.62	3.27
	m^3 (loose)/PSH$_0$	143.74	18.87
	m^3 (loose)/PSH$_{15}$	141.20	22.37
Costs	€/t	9.02	1.47
	€/m^3(loose)	1.32	0.21

Note: PSH$_0$ = Productive Machine Hours, excluding all delays; PSH$_{15}$ = Productive System Hours, including delays up to 15 min.

Machine cost calculation showed that the total costs of the observed system (star screen and wheel loader) are 182 €/PSH$_{15}$ (Table 3). Using a given system productivity of 20.99 t/PSH$_{15}$, total screening costs amount to 9.02 €/t, based on the amount of unscreened chips.

3.2. Product Analyses

The mean incidence of the tree components under different fine screen settings before and after screening is shown in Table 5. Before screening, the fresh logging residue chips contained 55.6% of fibers, 15.1% of needles, 14.5% of bark, 10.8% of twigs, and 4% of “others” (very small particles and contamination with inorganic particles), on average. The unscreened material did not differ significantly in terms of component composition between the different treatments. After screening, the needle content of the medium fraction was significantly lower than that of the unscreened material at rotation speeds of 1861 and 2239 rpm. However, no significant reduction of the needle content was found at a rotation speed of 2624 rpm. The results further indicated that screening seemed to increase the amount of fibers and lower the proportion of contaminants and very small particles (category “others”), but these differences were not significant in statistical terms. The fine fraction represented the pile with the highest needle and lowest fiber content. The proportions of both components differed significantly from the unscreened material.

Table 5. Fiber, bark, twig, and needle contents of the woodchip samples (%) before and after screening.

			Unscreened Woodchips	Screened Fraction		
				Fine	**Medium**	**Coarse**
Setting of the Fine Screen Deck	**1861 rpm (n = 8)**	Fibers	58.23 ^{a}	18.27 ^{b}	69.16 ^{ac}	78.79 ^{c}
		Bark	13.22 ^{a}	15.29 ^{a}	12.87 ^{a}	7.85 ^{a}
		Twigs	11.75 ^{a}	6.02 ^{a}	9.68 ^{a}	10.94 ^{a}
		Needles	13.32 ^{a}	52.93 ^{b}	5.84 ^{c}	1.43 ^{d}
		Others	3.48 ^{a}	7.48 ^{b}	2.46 ^{a}	0.99 ^{a}
	2239 rpm (n = 7)	Fibers	58.70 ^{a}	13.17 ^{b}	62.99 ^{ac}	76.47 ^{c}
		Bark	15.56 ^{a}	12.44 ^{a}	16.66 ^{a}	12.63 ^{a}
		Twigs	8.19 ^{a}	5.48 ^{a}	11.76 ^{a}	8.10 ^{a}
		Needles	14.07 ^{a}	52.62 ^{b}	6.09 ^{c}	1.92 ^{d}
		Others	3.49 ^{a}	16.29 ^{b}	2.50 ^{ac}	0.88 ^{c}
	2624 rpm (n = 8)	Fibers	50.16 ^{a}	9.93 ^{b}	48.78 ^{a}	68.62 ^{a}
		Bark	14.98 ^{a}	13.33 ^{a}	11.81 ^{a}	9.81 ^{a}
		Twigs	12.17 ^{ab}	4.03 ^{a}	17.57 ^{b}	16.10 ^{ab}
		Needles	17.68 ^{a}	59.64 ^{b}	17.38 ^{a}	3.58 ^{c}
		Others	5.02 ^{a}	13.06 ^{b}	4.47 ^{a}	1.89 ^{a}

Note: Values represent % incidence on total sample mass (on a dry basis); Values in the same row not sharing the same supscript letter are significantly different at $p < 0.05$ in the equality for column means.

Screening seems to improve particle size distribution by increasing the proportion of acceptable particles and decreasing that of fine and oversize particles (Table 6). However, the quality of removing fines and oversize particles largely depended on the screen settings. The usage of a fine screen setting of 1861 rpm led to the highest proportion of acceptable particles (84.4%) in the medium fraction, which differed significantly from that of the unscreened material (69.1%). Treatments with higher rotation speeds were not able to significantly increase the proportion of acceptable particles compared with the unscreened woodchips. Fines were particularly abundant in the fine fraction, representing 69% to 81% of its total mass. However, it was not possible to remove all fine particles from the woodchips. Only at a fine screen setting of 1861 rpm could a significant reduction of the fine particles from 22.9% to 8.4% be observed.

Table 6. Particle size distribution of the woodchip samples before and after screening.

				Fines, % (<3.15 mm)	Acceptable, % (3.15–63 mm)	Oversize, % (>63 mm)
Setting of the Fine Screen Deck	**1861 rpm** (n = 8)	**Unscreened Woodchips**		22.86 ^{a}	69.06 ^{a}	8.09 ^{a}
		Screened	Fine fraction	71.78 ^{b}	28.22 ^{b}	0.00 ^{a}
			Medium fraction	8.44 ^{c}	84.42 ^{c}	7.15 ^{a}
			Coarse fraction	1.90 ^{c}	49.26 ^{d}	48.85 ^{b}
	2239 rpm (n = 7)	**Unscreened Woodchips**		22.24 ^{a}	68.19 ^{ac}	9.58 ^{a}
		Screened	Fine fraction	69.10 ^{b}	30.90 ^{b}	0.00 ^{a}
			Medium fraction	8.97 ^{ac}	80.92 ^{a}	10.11 ^{a}
			Coarse fraction	2.14 ^{c}	54.07 ^{c}	43.79 ^{b}
	2624 rpm (n = 8)	**Unscreened Woodchips**		25.93 ^{a}	66.71 ^{a}	7.35 ^{a}
		Screened	Fine fraction	80.56 ^{b}	19.44 ^{b}	0.00 ^{a}
			Medium fraction	23.88 ^{a}	71.16 ^{a}	4.83 ^{a}
			Coarse fraction	5.55 ^{c}	53.15 ^{c}	41.29 ^{b}

Note: Values represent % incidence on total sample mass (on a dry basis); Values in the same column not sharing the same supscript are significantly different at $p < 0.05$ in the equality for column means.

Moisture content was calculated for the unscreened woodchips directly before and for the three screened fractions directly after screening (Table 7). The average moisture content of the green, unscreened chips was 44.6%. There was no significant difference in moisture content of the unscreened chips between the treatments before screening. However, differences were detected between the different fractions after screening. At all screen settings, the moisture content of the coarse fraction was significantly lower than that of the fine and medium fraction. Moisture content was always highest at the fine fraction.

Table 7. Moisture, ash, energy, and nutrient contents before and after the screening operations.

			Unscreened	Screened Fraction		
				Fine	Medium	Coarse
Setting of the Fine Screen Deck	1861 rpm (n = 8)	Moisture content (%)	46.42 ^{ab}	56.97 ^{a}	52.09 ^{a}	41.41 ^{b}
		Ash content (%)	2.70 ^{a}	7.65 ^{b}	2.36 ^{a}	1.29 ^{a}
		Energy content (MJ/kg)	20.6 ^{a}	20.4 ^{a}	20.7 ^{a}	20.6 ^{a}
		Nutrient content:				
		C (%)	51.1 ^{a}	47.8 ^{b}	52.4 ^{c}	52.6 ^{c}
		N (ppm)	3727 ^{a}	7139 ^{b}	2963 ^{ac}	2477 ^{c}
		P (ppm)	300 ^{a}	543 ^{b}	241 ^{a}	223 ^{a}
		K (ppm)	1094 ^{a}	1614 ^{b}	948 ^{a}	1082 ^{a}
		Ca (ppm)	3954 ^{a}	6147 ^{b}	3701 ^{a}	3157 ^{a}
		Mg (ppm)	511 ^{a}	781 ^{b}	483 ^{a}	403 ^{a}
	2239 rpm (n = 7)	Moisture content (%)	45.64 ^{ab}	50.97 ^{a}	48.36 ^{a}	42.87 ^{b}
		Ash content (%)	3.56 ^{a}	16.29 ^{b}	2.70 ^{a}	1.41 ^{a}
		Energy content (MJ/kg)	20.4 ^{ab}	19.0 ^{a}	20.5 ^{ab}	20.6 ^{b}
		Nutrient content:				
		C (%)	51.0 ^{a}	47.9 ^{b}	52.2 ^{c}	52.4 ^{c}
		N (ppm)	3708 ^{a}	7777 ^{b}	3193 ^{ac}	2549 ^{c}
		P (ppm)	295 ^{a}	588 ^{b}	271 ^{a}	231 ^{a}
		K (ppm)	1086 ^{a}	1708 ^{b}	1056 ^{a}	1116 ^{a}
		Ca (ppm)	4111 ^{a}	6223 ^{b}	4248 ^{a}	3687 ^{a}
		Mg (ppm)	512 ^{a}	841 ^{b}	532 ^{a}	433 ^{a}
	2624 rpm (n = 8)	Moisture content (%)	41.80 ^{a}	55.62 ^{b}	52.92 ^{b}	47.11 ^{a}
		Ash content (%)	4.30 ^{a}	10.53 ^{b}	3.34 ^{a}	2.24 ^{a}
		Energy content (MJ/kg)	20.6 ^{ab}	19.6 ^{a}	20.5 ^{ab}	20.7 ^{b}
		Nutrient content:				
		C (%)	50.8 ^{a}	47.7 ^{b}	52.0 ^{c}	52.3 ^{c}
		N (ppm)	4298 ^{a}	8053 ^{b}	4670 ^{a}	3055 ^{c}
		P (ppm)	350 ^{a}	610 ^{b}	384 ^{a}	279 ^{a}
		K (ppm)	1236 ^{a}	1751 ^{b}	1330 ^{a}	1229 ^{a}
		Ca (ppm)	4473 ^{a}	6436 ^{b}	4459 ^{a}	3737 ^{a}
		Mg (ppm)	576 ^{ac}	856 ^{b}	639 ^{a}	481 ^{c}

Note: Values in the same row not sharing the same supscript are significantly different at $p < 0.05$ in the equality for column means.

The ash levels corresponding to each screening level and screen setting are of primary concern for evaluating the quality of the material. Screening showed no significant reduction in ash content for all three treatments. The ash content of the fine fraction, however, was significantly higher than that of the unscreened material and the medium and coarse section, ranging from an average of 7.65% at a fine screen setting of 1861 rpm to an average of 16.29% at a fine screen setting of 2239 rpm. For all treatments, the coarse fraction showed the lowest ash contents, which differed significantly from that of the fine fraction, but not from the medium fraction and the unscreened material.

The energy content of the screened medium fraction did not differ significantly from the unscreened material. Differences between the different material streams and the different treatments appear to be very small. The screened fine fraction was shown to contain the lowest energy content, which, however, did not differ significantly from the unscreened material.

Elemental analyses were also performed for the different material streams. The highest nutrient concentrations were found to be in the fine fraction. All analyzed macronutrients of the fine fraction had a significantly higher nutrient concentration than the unscreened material. However, screening only led to a slight reduction of nutrient contents in the medium fraction, which turned out to be non-significant.

3.3. Cost-Benefit Comparison

The rotation speed of the fine stars largely influences the quality of the screened material. High quality woodchips are usually characterized by a low ash content, a high energy content, and a low proportion of fine particles. Moreover, from an ecological perspective, most of the nutrients should be left on the forest site, which means that woodchips should contain low needle and nutrient contents. In our study, these requirements were mostly met at a rotation speed of 1861 rpm. However, even with this setting, the majority of the quality parameters did not differ significantly from the unscreened woodchips.

Generally, the results indicate that a reduction of the rotation speed has a positive impact on the quality of the screened chips (Table 8). At the same time, low rotation speeds led to a reduced discharge of medium fraction chips, resulting in increased screening costs, calculated on the amount of chips of the medium fraction. Differences between screening costs were highest between a rotation speed of 1861 rpm and 2239 rpm. At the same time, the quality improvement by reducing the speed from 2239 rpm to 1861 rpm was comparatively low.

Table 8. Screening costs and selected characteristics of the screened woodchips (medium fraction) corresponding to different settings of the star screen.

	Setting of the Fine Screen Deck		
	(1861 rpm)	**(2239 rpm)**	**(2624 rpm)**
Screening Costs [1] (€/t)	14.05	12.36	11.47
Incidence of Acceptable Particles [1] (%)	**84.42**	80.92	71.16
Av. Energy Content [1] (MJ/kg)	20.68	20.46	20.45
Av. Ash Content [1] (%)	2.36	2.70	3.34
Av. Nitrogen Content [1] (ppm)	2963	3193	4670
Av. Needle Content [1] (%)	5.84	6.09	17.38

[1] Values refer to the amount of screened woodchips (medium fraction) Bold values differ from the unscreened woodchips at a significance level of 5%.

4. Discussion

Our results indicated that the screening of green woodchips with a star screen with the fine screen deck set to 1861 rpm or 2239 rpm can significantly reduce the needle content of the screened medium fraction, which positively influenced material characteristics like ash content and particle size distribution. The highest setting of the fine screen deck (2624 rpm) did not significantly change the needle content relative to the unscreened woodchips.

The ash levels measured with chipped, green woodchips fall within the typical range of the literature [31] and are likely a product of contaminants introduced during harvesting and chipping operations. However, wood ash often comprises high concentrations of heavy metals, which may exceed national limit values for maximum allowable heavy metal concentrations for fertilizers [32] and consequently needs to be brought to a landfill. Thus, from a cost perspective, the amount of ash produced should be minimized in order to decrease both maintenance costs at the heating plants and disposal costs. The present study showed that the use of star screens leads to a reduction of the amount of ash produced by heating plants. At all screen settings, the ash content of the fine fraction was significantly higher than that of the medium fraction. Nevertheless, no significant differences of the ash content between the unscreened and the screened medium fraction could be observed at any screen setting.

For small heating plants, particle size distribution is one of the most important quality parameters because they are very sensitive to fine and oversize particles. Long, irregular particles are often problematic, as they may cause blockages and hinder the firing process. In contrast, fine particles reduce the air circulation within the woodchip piles, which decreases drying speed and increases the risk of self-combustion and spore formation due to microbial activity and fungal infestation [21]. Previous studies on screening machines already have shown that it is possible to remove fine and/or oversize particles [14,20–23]. However, the machines tested within these studies differed in terms of throughput capacity and working principle: trommel screens and vibrating desks are only able to remove fine particles from the material stream, whereas star screens are able to separate woodchips into three fractions. Thus, star screens offer advantages, since they are able to remove fine and oversize particles at once. Nevertheless, the study hints at a substantial reduction of coarse particles (>63 mm). Even after screening, the medium fraction contained 5% to 10% of coarse particles on average, indicating that there is a strong need to adjust the coarse screen settings to obtain less oversize particles at the medium fraction after screening.

Our results indicate that the moisture content of the woodchips may also influence the quality of the screening process in terms of particle size distribution. Within this study, it was not possible to remove all needles, which usually represent small particles that belong to the fine fraction. On average, 20% to 40% of the needles were not detected as fine particles by the screen at the different settings. One cause for this inefficient separation is the fact that green logging residue woodchips constitute a high content of needles, which are mostly still attached to the branches. While some needles fall off the branches during screening, others remain attached and are treated as large particles together with the branches. During drying, the needles start to fall off the branches, which increases the proportion of fines within the piles of the medium and coarse fractions.

Knowing this fact, one could assume that it would be best to let the green chips dry at the terminal before screening. However, this approach would lead to increased drying times of the woodchips, since the high portion of fine particles within the piles hamper air circulation. As a result, higher storage capacities would be required due to both the reduced drying speed of the woodchips and the higher amount of material due to the additional presence of fine and coarse particles within the piles.

Another approach would be to let the logging residue piles dry at roadside landings before chipping and screening. In this case, parts of the needles would fall off the branches and remain at the roadside, reducing the amount of fine particles in the woodchips [33,34]. Furthermore, low moisture contents of the material would lead to a reduction of the procurement costs, since transportation costs are largely influenced by the moisture content of the transported material [35]. However, the drying performance of logging residue brush piles depends on numerous factors such as air humidity, temperature, soil humidity and temperature, precipitation, solar radiation, and airflow velocity [36]. Especially at roadside landings, conditions for drying are often disadvantageous due to shade from surrounding trees [34]. Moreover, high contents of needles and fine branches reduce the airflow velocity within the piles. In particular, there have been a few studies dealing with the drying speed of logging residue piles at roadside landings, which reported different drying performances of brush piles [33,34,37,38]. Stampfer and Kanzian [37] reported that moisture content of logging residue piles decreased from 40–50% to 15–29% during summer, whereas analyses of Nurmi [33] showed only a slight decrease in moisture content from 56% to 42% within one year. However, also in this study, approximately one-third of the needles fell off during roadside storage. Based on these findings, it can be assumed that increased storage times very likely reduce the number of fine particles within the unscreened woodchips and may also facilitate the separation of needles and other fines during screening later on. Consequently, there is a strong need for further research to analyze both the impact of wood storage times and conditions on quality parameters of woodchips and the performance of screens dealing with drier logging residue woodchips.

Operationally, equipment utilization was high within this study—never falling below 90% for both machines, the star screen and the loader. However, it was not possible to make fundamental, reliable estimates of delay times due to the limited observation time of the system (ca. 8 h). More fundamental and accurate statements on delay times can only be obtained by long-term follow-up studies or by combining a larger number of machine category specific time studies [39]. Recent studies on screening machines showed much higher shares of delay times: Spinelli et al. [14] found a total share of delay times of ca. 25% during a time study of a small mechanical screen. The share of delay times during a time study of a grinder/trammel screen system, reported by Dukes et al. [23], was even higher, ranging from 34% to 60% of the total scheduled time. Thus, there is still a strong need to carry out long-term studies on machines that can be used to screen woodchips in order to achieve more reliable estimates of delay times.

From a cost perspective, screening of logging residues increased fuel production costs by 11 to 14 €/t, calculated on the amount of chips of the medium fraction. However, previous studies on other screening machines showed much higher costs. Spinelli et al. [14], who conducted a study on a mobile mechanical vibration screen, reported on total screening costs of 28.5 €/t, whereas Nati et al. [21], who analyzed the performance of a trommel screen, reported on screening costs ranging from 16.2% to 19.9 €/t.

At the time of writing, only a few studies were available on the mechanical screening of woodchips. It seems that the results strongly depend on the screening method, the screening type, and the raw material. Although most of the studies conclude that screening is a promising method to increase fuel quality, its use remains somewhat sporadic. So far, only little is known about screening productivity and costs. In particular, hardly any information is available on the implementation of the screening process in woodchip supply chains. Thus, there is a strong need for studies focusing on chip production systems that consider screening alternatives. Furthermore, little is known about potential uses of the fine fraction, which contains high concentrations of nutrients. There is a great need for studies focusing on application possibilities in regard to ecological soundness and economic feasibility.

5. Conclusions

Screening offers a cost-effective method to increase the quality of woodchips. In particular, the use of star screens offers big advantages, since fine and oversize particles can be removed from the chips in one step. The results of this study indicated that it is possible to increase the quality of woodchips by screening. In particular, star screens can be used to lower ash content and to remove particles of undesirable size classes. However, the tested star screen was primarily designed to work with compost and not with woodchips. Our results showed that modifications of the screen settings are still necessary to further increase the product quality before the machine can be used effectively with fresh logging residue woodchips.

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Publication IV

Evaluation of a modified centrifugal spreader to apply nutrient-rich fine fractions from woodchips as a fertilizer to cutover areas in steep terrain.

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Evaluation of a modified centrifugal spreader to apply nutrient-rich fine fractions from woodchips as a fertilizer to cutover areas in steep terrain

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Abstract

Whole-tree harvesting, where whole trees including branches and tops are extracted from the stand, had become more common in cable logging in Central Europe due to higher mechanization and lower harvesting costs compared to cut-to-length or stem-only harvesting. After whole-tree-harvesting, slash piles, which mainly consist of the nutrient-richest parts of the trees, remain close to the forest road. As an energy source, these logging residues often cause problems during thermal conversion due to their high portion of fines. Screening experiments already demonstrated that it is possible to achieve a high quality raw material by separating fines after chipping. Within this study, we focused on the rejected fines, which mainly consist of the nutrient richest parts of the trees like needles, twigs and bark. The objective of this study was to evaluate a novel method to return these nutrient-rich fractions back to steep slopes using a modified spin-type spreader.

Field tests were performed to evaluate mass distribution for the spreader, which was attached to the mainline of a carriage. Tests showed that spreading distances up to 9 m (26 ft) to either side of the spreader are achievable under field conditions. Segregation of the different tree compartments (needles, twigs, fibers, bark) was marginally. Regression analysis showed that the productivity of the spreader was widely correlated with the moisture content of the material. A high moisture content lowered the flow properties of the material resulting in lower productivities and higher system costs.

Keywords: Application uniformity, distribution uniformity, spin-type spreader, steep terrain

1 Introduction

48% of Austria’s land surface is covered by forests, whereof 18% of the forest area is characterized by slopes steeper than 60% (BFW, 2013). To carry out harvesting operations in mountainous areas is not only complex because of steep slopes but also because of broken terrain and low road network density, which limits the accessibility with ground based harvesting machinery and increases harvesting costs (Visser & Stampfer, 2015). Today, tower yarders represent the state of the art technology for efficient steep terrain harvesting in Central Europe. Technical developments and system optimizations during the last few decades led to more efficient and socially acceptable ways to carry out cable logging. The development of processor tower yarders, which are equipped with boom-mounted processor heads, was one of the most important steps in the history of cable logging, which enables them to work cost-efficiently with whole-tree harvesting (WTH). Heinimann et al. (2001) estimated, that the use processor tower yarders results in cost savings of about 40 % compared to motor-manual cut-to-length systems (CTL). As a consequence, WTH, where delimbing takes place at the roadside using processor-heads, had become more common in cable yarding in Central Europe. This local shift of the delimbing process from within the forest to the roadside inevitably results in an increased removal of nutrients, since fine branches and needles contain a high proportion of a tree’s nutrients (Lick, 1989).

With the development and increased use of WTH, concerns about nutrient sustainability had immediately been raised (Tamm, 1969; Mälkönen, 1976). Since then, a large number of studies focusing on the impact of WTH on tree growth (Jacobson et al., 2000; Tveite & Hanssen, 2013), base cation status (Olsson et al., 1993) and acidification (Nykvist & Rosén, 1985) have been carried out. Conclusions from studies evaluating WTH effects of individual sites have varied widely. However, the majority of the studies concluded that WTH can endanger long-term site productivity.

In response to the outcome of these studies, tree-topping treatments have been included in the harvesting guidelines of many Austrian forest companies to reduce negative impacts on site productivity due to WTH. However, the ecological impact of topping treatments in WTH mainly depends on both the topping diameter and the stand density. Case studies of Huber (2015) showed that the effect of topping on the amount of biomass remaining in the stand is limited to approximately 50% of the crown biomass (branches and needles) of the harvested trees. Consequently, especially on sites with poor nutrient supply, topping treatments may not always be sufficient to prevent productivity losses. Hence, there is a need to develop methods and measures to increase the nutrient supply of forest sites as cost-effective as possible.

On easy accessible terrain, fertilization is a common method to increase the nutrient supply of forests in many countries (Ring et al., 2013). Both, mineral and organic fertilizers can be used for fertilizing. Mineral fertilizers are usually preferred because of their known chemical and physical properties and their cost-effective means of application. In contrast, organic fertilizers are characterized by long lasting release of nutrients, which minimizes the number of applications within a certain time. However, in mountainous regions, the steepness of the terrain limits the accessibility by machinery and thus largely prevents mechanized fertilization.

Within this context, the Austrian cable-yarder manufacturer “Mayr-Melnhof” has developed an entirely new method to apply organic fertilizer to inaccessible terrain, depending on the requirements of a stand. The aim of this study was to determine the performance of this new method in terms of productivity and application quality.

2 Materials and Methods

2.1 The prototype spreader

The spreader tested in this study was a Rauch Axeo 6.1, which is normally used in winter to apply salt, grit or sand to snow-covered, icy roads in order to ensure road safety. The spreader is equipped with one hydraulically controlled spinner disc with eight uniformly spaced vanes, which spread the material up to 8 m (26 ft) far away. A rotating agitator inside the 0.6 m^3 (21 ft^3) hopper feeds the material through an adjustable guillotine gate onto the horizontal spinner disc and facilitates the delivery of the spreading material.

Figure 1: Modified centrifugal spreader attached to the mainline of a carriage

However, these municipal spreaders are originally designed to be powered by farm tractors, which are not suitable to drive on rough, steep slopes. Hence, tower yarders were used in this study to maneuver the spreader over areas, which are inaccessible by ground based machinery. Therefore, several modifications on the spreader were necessary (Fig. 1); Support arms were fixed to the spreader in order to attach the machine to the mainline of the carriage and a 7.5 kW (10 hp) diesel engine was attached to the spreader to provide independent power supply. Moreover, the spreader was fitted with a radio control system, which enables the operator to easily control the prototype from any position.

All test runs of this prototype were conducted at the end of cable logging operations at cutover areas. During the entire test of the prototype, the guillotine gate was set at a maximum opening of 130 cm^2 (20 in^2). The flow control valve for the spinner disc was open all the way, giving a spinner speed of approximately 400 rpm. At the beginning of each test run, the spreader hopper was filled to approximately 80 to 90% of its total capacity. The spinner speed of the fully loaded spreader at the beginning of each spreading cycle was somewhat lower due to the high power requirement of the agitator, which is directly connected with the spinner disc.

Fines of previously screened wood chips from logging residues were used in this study. Screening of low quality woodchips is a frequently discussed topic and is sometimes used to increase wood chip quality in order to both enhance fuel-handling quality and to achieve a better price (Spinelli, 2011). Actually, rejected fines, which largely consist of nutrient-rich needles, are usually used in composting plants. Consequently, the underlying concept of this study was to return the fines back to the forest sites as a fertilizer instead of composting in order to increase the nutrient pool of forests. This material was stored in 0.50 m^3 (18 ft^3) and 1 m^3 (35 ft^3) big bags for varying periods both outdoors and covered, so that the test materials differed significantly in terms of moisture content.

2.2 Spreader evaluations and analysis in terms of distribution uniformity

Round buckets, with a diameter of approximately 265 mm (10 in.) and a total capacity of 10.6 l (2.8 gal.), were placed across the swath in lines perpendicular to the travel direction of the spreader (Fig. 2). Each row consisted of a linear series of 25 buckets (12 on each side and one beneath the cable line), which were located 1 m (39 in.) away from each other. Small, washed stones were put into the buckets to prevent them from tipping over by the wind.

Figure 2: Test setup for evaluating the distribution pattern of the prototype spreader broadcasting organic fertilizer

The boom of the cable yarder was used to lift and position the filled big bags directly above the hopper of the prototype spreader. Subsequently, the material was released from the big bags to the hopper through a discharge scout at the bottom of the big bags. As soon as the material was being loaded into the spreader, a single 9.5 l (580 in^3) grab sample was collected to determine moisture content and particle size distribution. The fully loaded spreader then started to spread the material onto the study area. The number of passes depended on the flow rate of the material and was thus highly variable between the cycles. At the beginning of the fertilization experiments, the ground clearance, defined as the distance from the ground to the spinner disc of the fully loaded spreader, was measured at the position of each bucket row.

Both the samples from the hopper and the buckets were weighed on-site and analyzed for moisture content according to EN ISO 18134-2. Additionally, the whole samples collected from the big bags at the beginning of each spreading cycle were run for particle size distribution according to EN 15149-1:2010 using a one dimensional horizontal screening device model GFL 3016. The sieve shaker was working with an amplitude of 30 mm (1.18 in) and a frequency of 275 rpm. Six sieves with a diameter of 200 mm (7.87 in.) were used to separate the following chip length classes: >100mm, 64-100 mm, 45-64 mm, 16-45 mm, 8-

16 mm, 3.15-8 mm, 1-3.15 mm, <1 mm (>3.94 in, 3.94-2.48 in, 2.48-1.77 in, 1.77-0.63 in, 0.63-0.31 in, 0.31-0.12 in, 0.12-0.04 in, <0.04 in).

The d_{16}, d_{50} and d_{84} particle sizes were used to report the median particle size (d_{50}) and to calculate the Granulometric Spread Index (GSI) for the collected material of each pan to provide the size distribution range.

The dry mass of the material collected in the buckets was used to evaluate distribution uniformity, which was assessed by calculating a coefficient of variation (CV), including simulated overlap of the spreading patterns for different cable line spacings (ASABE Sandards, 2009).

2.3 Time study

The time study of the prototype-spreader was carried out manually using a handheld computer (Algiz 7). The working time was recorded using the continuous timing method, by which the time of each work phase shift is noted and the duration of each phase is calculated by subtracting two time marks. Effective working time was divided into the following time phases:

- Filling: Begins when the big bag is attached to the hook of the crane and ends as soon as the spreader is fully lifted to the carriage ready for spreading.
- Spreading: Begins when the first particles are spread out and ends as soon as the material flow stops.
- Empty drive: Begins when the material flow has stopped and ends as soon as the spreader touches the ground at the landing.
- Delay: Time not related to effective work (e.g. breaks, repair work)

In total, 22 working cycles were recorded within this study. Additionally, the weight of each big bag was estimated before and after the filling of the spreader, using a crane scale with an accuracy of 0.5 g (0.018 oz).

2.4 Time consumption analysis

The time consumption data set was associated with the payload of the spreader to assess its productivity, which was defined as the amount of spread material per hour working time (odt PSH_0^{-1}). Delays were excluded from this study due to the limited number of replications, which impede reliable estimates of delay times.

To assess the influence of material properties (median particle size, moisture content) on the productivity of the spreader, regression analysis was performed. The variables were introduced to the model using the forward stepping procedure. Before analysis, the data was tested for outliers and normality to check if the underlying statistical requirements are met. All analyses were carried out with the statistical software IBM SPSS 21 using a significance level of $p=0.05$.

3 Preliminary results and discussion

3.1 Fertilizer characterization

The main characteristics of the bulk sample analyses are presented in table 1. The median particle size (d_{50}), the ganulometric spread index and the compartment weights are provided. The spread material was characterized by a median particle size of 1.86 mm (0.078 in) with a GSI-value of 113, which indicates a high variability in particle size distribution. The material mainly consisted of needles, which made up more than one third of the total weight. Other nutrient-rich tree compartments like bark or twigs accounted together for approximately 17% of the total weight. The category “fine particles”, which contains particles smaller than 1 mm (0.047 in), mainly comprises needle and bark particles. However, a specific allocation of the particles of this fraction to different tree compartments was not possible due to their small size. The moisture contents of the material filled into the spreader for broadcasting varied from 15% to 54% due to different storage durations and conditions (covered by semipermeable fabrics, canopied, stored outside, …).

Table 1: Means and standard deviation (SD) of the median particle size (d_{50}), the GSI and the compartment composition of the material. The values are based on 6 randomly chosen bulk samples.

Material characteristics	*Mean*	*SD*
d_{50}[a](mm)	1,86	0,27
GSI[b]	112,84	21,03
Needles (kg t^{-1})	347,17	80,54
Bark (kg t^{-1})	134,41	44,96
Twigs (kg t^{-1})	36,70	18,74
Fibers (kg t^{-1})	186,96	69,82
Fine particles[c] (kg t^{-1})	197,55	43,07
Stones (kg t^{-1})	97,2	59,28

[a] d_{50} is the median particle size for the fertilizer sample
[b] GSI represents the Granulometric Spread Index
[c] Fine particles comprise all particles smaller than 1 mm

3.2 Distribution uniformity analysis

No significant influence of both the vertical distance between spreader and ground and the moisture content on the distribution of the material could be observed. Hence, the mean application rate across the swath width for all 24 analyzed spread patterns is shown in figure 3. Application rate varied significantly along the swath representing a bell-shaped single spread pattern. Most particles landed close to the travel path of the spreader resulting in high application rates. However, most of the material landed within a distance of 7 m (23 ft) to either side of the center of the spreader.

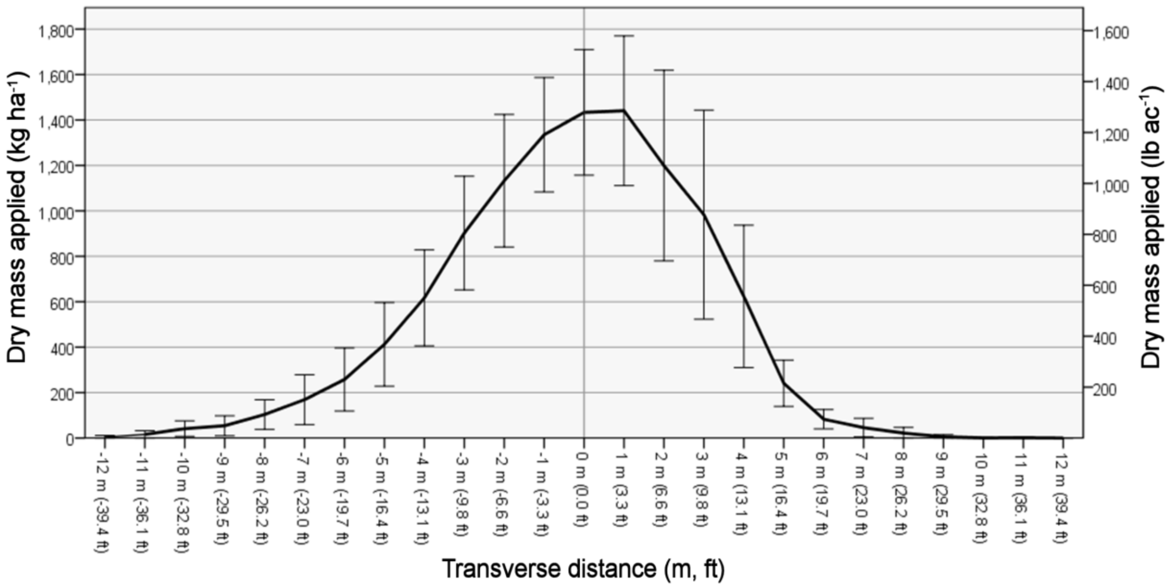

Figure 3: Mean dry mass distribution pattern. The error bars indicate the range of fluctuations for a confidence range of 95%.

Particle size variability across the swath width is presented in table 2. Medium and small particles were predominantly applied directly beneath and close to the travel path of the spreader. In contrast, most of the larger particles were applied farther from the center up to a distance of approximately 8 m (26.2 ft). The median particle size decreased rapidly at a swath width of approximately 9 m (29.5 ft). Presumably, the trajectory of the small particles, which landed beyond this distance, was influenced by wind action. The Granulometric spread index (GSI) indicated a continuously high particle size variability all across the swath width.

Table 2: Summary of mass and particle size analysis by transverse position

Transverse distance		***Mean Application rate***		***d50[a]***		
m	***ft***	***kg ha^{-1}***	***lb ac^{-1}***	***mm***	***in***	***GSI[b]***
-12	-39.4	4	4	1.03	0.040	145
-11	-36.1	16	14	1.25	0.049	120
-10	-32.8	41	37	2.29	0.090	88
-9	-29.5	54	48	1.73	0.068	93
-8	-26.2	104	93	1.76	0.069	97
-7	-23.0	169	151	1.64	0.065	116
-6	-19.7	258	230	2.40	0.095	111
-5	-16.4	412	368	2.41	0.095	123
-4	-13.1	617	550	2.34	0.092	103
-3	-9.8	902	805	2.09	0.082	117
-2	-6.6	1133	1010	2.12	0.083	110
-1	-3.3	1335	1191	1.84	0.072	101
0	0.0	1434	1279	1.80	0.071	101
1	3.3	1441	1285	2.04	0.080	96
2	6.6	1199	1070	2.44	0.096	89
3	9.8	983	877	2.76	0.109	100
4	13.1	624	556	2.81	0.110	87
5	16.4	241	215	2.77	0.109	98
6	19.7	83	74	2.24	0.088	105
7	23.0	46	41	3.62	0.143	68
8	26.2	22	19	1.69	0.067	150
9	29.5	6	5	0.89	0.035	111
10	32.8	1	1	0.50	0.020	68
11	36.1	1	1	0.50	0.020	68
12	39.4	0	0	-	-	-

[a] d_{50} is the median particle size for the fertilizer
[b] GSI represents the Granulometric Spread Index

The results for the distribution uniformity for simulated swath widths are shown in figure 4. CV values increased uniformly up to a swath width of 17 m (55.8 ft) where the CV function slowly started to flatten out. CV values for all tree compartments turned out to be similar, which indicates that tree compartment segregation occurred only marginally. Only the twigs showed significantly higher CV values, especially for small swath widths.

According to previous findings from agricultural case studies, a CV value of less than 20% (Fulton et al., 2005) or 15% (Smith et al., 2000) is reported as acceptable. On the basis of the findings of the present study, distances between cable lines should not exceed 5 m (16.4 ft) to comply with these thresholds. In fact, distances between cable lines usually are much larger, ranging from 20 to 30 m, which would result in CV values of far more than 100%.

Nevertheless, although there is still a need to increase the spreading distance, the use of carriage-mounted spreaders constitutes a promising approach to ensure sustainability in forest management.

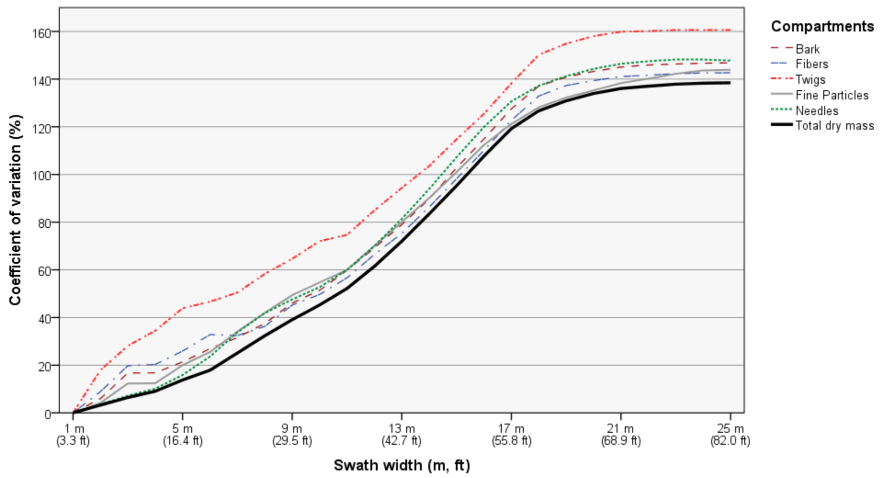

Figure 4: Coefficient of variation for each tree compartment and the total dry mass simulated for overlapping swaths with spacings from 1 to 25 m (3.3 to 82 ft)

3.3 Productivity analysis

While the empty drive of the spreader accounted for only 4.78% of the total effective working time, the proportions of filling and spreading time took 25.69% and 69.53% on average, respectively. The mean cycle time was 23.05±15.65 min. Figure 5 shows that the time consumption for filling the hopper of the spreader and spreading out the material was highly variable. There are several reasons for this. On the one hand, the material was stored in big bags of different design: While some big bags, which had to be emptied by shoveling, had a flat bottom, others were equipped with an outlet spout at the bottom side, which considerably facilitated and accelerated emptying the big bags. On the other hand, differences in moisture content of the material could also have influenced filling time consumption. Moist material increased the tendency to bridge over the outlet spout, which led to an interruption of the material flow and required further action.

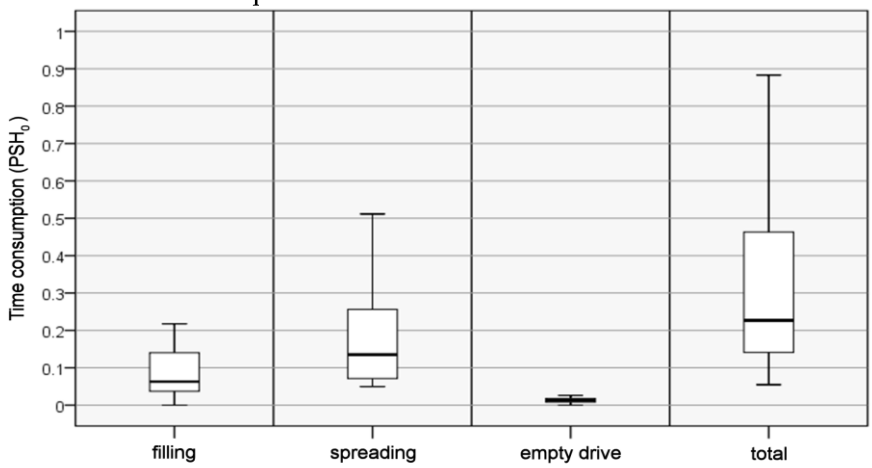

Figure 5: Time consumption of the main work elements and in total

For spreading time consumption, a significant impact of the moisture content was found (Eq. 1; R^2=0.514; *p*-value=0.001). Within the present study, high moisture contents of the material usually resulted in both lumping and bridging which hampered material flow and considerably reduced the productivity of the spreader. However, the material flow never stagnated completely due to the permanent mobilization of particles by the agitator, which also generated moderate vibrations of the hopper that additionally improved the flow properties of the material. Regression analysis also showed that neither the median particle size nor the number of passings had a significant impact on spreading productivity.

$$Eff_{spreading}\ [PSH_0\ t^{-1}]=4.736 - 0.282 * MC[\%] + 6.092*10^{-3} * MC[\%] \qquad (1)$$

Both the observed values and the model estimates are presented in figure 6. The model shows that the time consumption for spreading out the material increases as soon as the moisture content of the material exceeds 35%. The prototype spreader reached its maximum productivity at a moisture content of 32%. Test runs with drier materials resulted in a somewhat lower spreading productivity. A probable reason for this is that the good flow properties of the dry material in combination with high vibrations generated by the agitator resulted in a high compaction of the material inside the hopper, which reduced the spinner speed due to higher power supply.

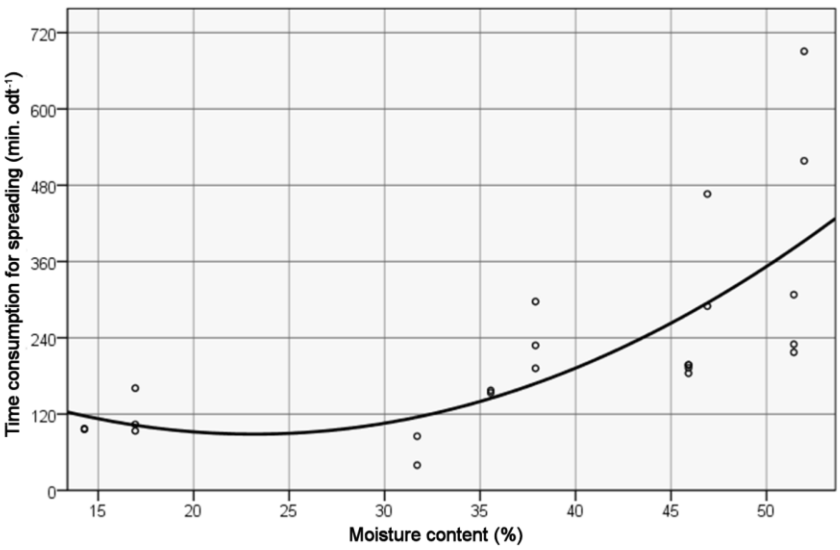

Figure 6: Effect of different moisture contents of the material on spreading efficiency

4 Summary and conclusions

A study was conducted to evaluate the distribution characteristics and the productivity of a novel method to broadcast fine rejects from woodchip screening operations at a cutover area in steep terrain using a modified centrifugal-type spreader. Distribution uniformity was evaluated based on mass concentrations and productivity of the spreader was determined based on time studies.

The following conclusions were reached based on the results of this investigation:

- Most of the material landed within a distance of 7 m (23 ft) to either side of the center of the spreader.
- The distance between spreader and ground had no significant impact on the spreading distance.
- The proportion of larger particles slightly rises with increasing swath width up to a spreading distance of approximately 9 m (29.5 ft).
- The time consumption for spreading significantly depends on the moisture content of the material. The prototype had its highest productivity at a moisture content of 32%. The productivity results indicate that broadcast application of fresh material should be avoided.

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