IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Mathematical Modelling of Engineering Problems
Vol. 11, No. 3, March, 2024, pp. 745-753
Journal homepage: http://iieta.org/journals/mmep

Efficient Technologies for Harvesting and Reutilizing Logging Residues in Russia: A Sustainable Forestry Approach

Ol'ga Kunickaya[1*], Michael Zyryanov[2], Sergey Medvedev[3], Aleksander Mokhirev[4], Anastasia Spiridonova[5], Pavel Perfiliev[6], Aleksei Teppoev[7]

[1] Department of Technology and Equipment of Forest Complex, Arctic State Agrotechnological University, Yakutsk 6770076, Russian Federation
[2] Department of Information and Technical Systems, University Branch of Siberian State University in Lesosibirsk, Lesosibirsk 662543, Russian Federation
[3] Department of Economic and Natural Sciences Disciplines, Reshetnev Siberian State University of Science and Technology, Lesosibirsk 662543, Russian Federation
[4] Department of Highways and Urban Structures, Siberian Federal University, Krasnoyarsk 660037, Russian Federation
[5] Department of Operation of Road Transport and Car Service, North-Eastern Federal University, Yakutsk 677000, Russian Federation
[6] Department of Timber Industry and Materials Processing, Northern Arctic Federal University, Arkhangelsk 163002, Russian Federation
[7] Department of Mathematical Methods in Management, Saint-Petersburg State Forest Technical University, Saint-Petersburg 194021, Russian Federation

Corresponding Author Email: olkunickaya3541@rambler.ru

https://doi.org/10.18280/mmep.110319

Received: 14 September 2023
Revised: 3 December 2023
Accepted: 15 December 2023
Available online: 28 March 2024

Keywords:
biofuel production, fire risk reduction, forest protection methods, logging, mechanised harvesting of logging residues, recycling, waste, soil fertilization

ABSTRACT

This article explores the use of logging residues in forestry to reduce the risk of fires, prepare areas for planting new trees, and use them as a valuable resource for the production of wood biofuels. While traditional methods of logging residue disposal include incineration in piles or swaths, this study examines an alternative approach known as the continuous slash-and-burn method. This method, although limited to fire-hazardous periods due to the use of paraffin, has such advantages as minimal thermal damage to the soil and accelerated decomposition of felling residues. The residues are charred rather than burned completely, increasing soil fertilisation and reducing fire hazard. This feature makes them less attractive to insect pests. Modern logging companies increasingly prefer efficient logging equipment instead of gasoline saws since the former improves the management of logging residues. Manual collection of residues on large stumps allows for forming larger piles. However, this method creates problems when transporting them to processing centers, for example, to upper storage sites. Therefore, the development of innovative transportation methods is a promising direction for further research. Thus, logging residues is a raw material, which is primarily valuable for the production of wood biofuels. Energy efficiency in the collection, processing, and transportation of these residues is crucial for their practical use. The consumed energy should be lower than the energy content of the residues, ensuring the feasibility of converting them into wood biofuels.

1. INTRODUCTION

Chipping residues can be scattered and left within a logging site during cut-to-length (CTL) harvesting as the trees are felled and processed. In contrast, the whole-tree (WT) harvesting method involves processing or chipping whole trees on stairwells or the roadside. However, both methods produce a concentration of harvesting residues at these locations [1]. The amount of produced logging residue depends on several factors, including the harvesting method, the equipment, the type of harvested product, the tree species, site conditions, the plantation age, and diameter. Residue collection and reuse aid in reducing fire risk and the stages of site infrastructure development and planting [2]. However, leaves and small branches are a source of nutrients for forest biocoenosis. Their removal can negatively affect the soil and vegetation and it is crucial to limit it [3].

Effective management of logging residues is essential. This study aims to scrutinize the use of logging residues to reduce the risk of fires, promote effective development of territories, and contribute to sustainable forestry practices. In particular, the study investigates the potential benefits and challenges of felling residue management, including the impact of various logging methods and equipment on the concentration of residues. The long-term preservation of forest plantations, therefore, requires learning efficient ways to deal with logging residues.

2. TASKS AND METHODS OF HARVESTING LOGGING RESIDUES

Logging residue is typically defined as the crown portion of harvested trees (limbs, branches, assimilating apparatus, and tops) and fragments of broken trunks and splinters left on the logging site after logging operations [4]. Logging residues must be removed from the logging site under the requirements of Clause 12 (sub-clause k) of the Timber Harvesting Regulations and Timber Harvesting Specifics in Forest Districts Specified in Article 23 of the Forest Code of the Russian Federation, as approved by Order No. 993 of the Ministry of Natural Resources and Ecology of the Russian Federation dated 1 December 2020. The harvesting of logging residues from the logging site is motivated by three fundamental concerns.

The first point of concern is fire safety. In most cases, the presence of untreated logging residues on a logging site is the most important factor that significantly increases the likelihood of a downstream fire spreading upstream compared to a cleared logging site. A forest fire is also much more likely to start on an unclean logging site [5]. Sun-dried logging residues are an ideal combustible material, and small sparks, often of natural origin, can start a forest fire. When the ‘forest fire triad’ is triggered, an uncontrolled fire spread begins in the forest. It is especially important in areas with a distinctly continental climate, where the air has low humidity, high summer temperatures, and significant solar exposure [6]. In addition, more than half of the forests of the Russian Federation are located on permafrost (cryolithic zone forests), where soil biota activity is very low. This fact makes logging residues difficult to decompose into humus and increases the fire risk, even years after logging [7].

The second concern, the phytopathological aspect, is critical. It is especially relevant in areas where insect pest outbreaks are common. Large logging residues and stumps can provide food and a breeding ground for these pests’ larvae [8]. As a result, in addition to logging residues, it is necessary to pay attention to stumps, which in some cases must be treated to prevent insect pest reproduction. Bears, for example, can help this process by actively dismantling stumps and eating the larvae that live there [9].

The third concern is that logging residue collection promotes natural forest regeneration. When a dense layer of logging residues covers the surface of a logging site, seeds from seed trees have difficulty penetrating this layer [10]. However, even with artificial forest regeneration, which is becoming more widespread in the Russian Federation every year, a continuous carpet of logging residues will impede the planting of seedlings (saplings) with either bare root or container-grown systems [11].

The following methods are recommended for clearing logging residues, as listed in Order of the Ministry of Natural Resources and Environment of the Russian Federation No. 367 dated 27 June 2016 ‘On Approval of Types of Cutting Operations, Procedure, and Sequence of their Implementation, Form of the Process Map of Cutting Operations, Form of the Harvest Site Inspection Report and the Harvest Site Inspection Procedure’.

First, ‘arranging logging residues on skidding trails to strengthen them and protect the soil from severe compaction and damage during skidding’. This option is popular in the Russian Federation, particularly regarding logging operations carried out in logging areas with low potting soil-bearing capacity (categories III and IV) during the warm season. It is a common practice since more than half of the territory of this country’s forest fund is located precisely on potting soils of categories III and IV. Typically, this option of removing the logging residues is carried out concurrently with the basic logging operations. The crown portion of the tree is placed on the skidding trail in the cutting strip immediately after felling the tree, clearing its limbs, and trimming the top. Sometimes, especially in heavily loaded areas, a portion of the harvesting residue is transferred to the main skidding trail [12]. However, most logging residues are collected and deposited on the skidding trail during the basic skidding operation. Additional clearing can be required during the snow-free period because some branches break off when the trees fall and are dragged when the harvester operates.

This method of logging residue removal has two significant advantages. First, it strengthens the skidding trails’ driving surface, reducing rutting, soil and ground damage [13], and the load on the forest machine gearbox and fuel consumption. Moreover, this method destroys and tramples logging residues into the soil, rendering them non-combustible and unappealing to insect pests. Furthermore, this practice hastens their decomposition, improving forest soil and creating better conditions for subsequent forest regeneration (see Figure 1). It is also important to note that the crown of a tree contains approximately 70% of all minerals contained in the tree, so decomposing it effectively enriches the forest soil with the necessary minerals [14].

Figure 1. Crushed and indented logging residues on the skidding trail in the cutting strip (Krasnoyarsk Krai) [15]

Second, ‘collecting logging residues into piles and swaths and burning them in a fire-safe period’. Before delving into this method of felling residue clearance, it is important to understand the distinction between the terms ‘piles’ and ‘swaths’. Unlike the previous method [15], this one involves clearing logging sites after the basic harvesting operations have been completed.

Logging residues on cutting strips are manually collected in selective or clear-cut harvesting operations to preserve evenly spaced new growth of valuable tree species. This process is physically demanding and inefficient manual labour. The logging residues are piled up during manual collection [16]. Following clear-cutting without preserving the undergrowth of valuable species, logging residues can be collected using dedicated rake pickers, typically mounted on skidder tractors. In this case, the harvesting residues are collected in swaths along predetermined marks by the rake.

When there is a fire risk, these piles or swaths are burned one after the other, beginning at the periphery and working towards the centre of the logging site [15]. This approach, however, is not ideal for the following reasons. First and foremost, burning logging residues creates pockets of severe thermal stress on the soil, depriving the soil of its ability to support plant growth for an extended period. Furthermore, this method necessitates a significant amount of effort on the burners' part and a small amount of fuel to ignite the piles or swaths. Nevertheless, although the basic goals of clearing logging residues are met, they no longer pose a fire hazard and are of no interest to insect pests, and the ash helps improve forest soil fertility [17].

Third, 'collecting logging residues into piles and swaths and leaving them in place to decompose and feed wildlife during the winter'. The piles or swaths in this option are obtained under the same conditions and methods as in the previous option. The only difference is that piles are gathered on the stumps: big logging residues are laid down first, followed by a layer of small wood chips starting at 0.7 m. Following these recommendations is certainly impossible when gathering logging residues into swaths with a rake picker [18]. This option does not waste energy and money on burning and does not cause thermal damage to the soil. However, it does not guarantee the participation of piles or swaths in a forest fire if it occurs. In addition, the method does not protect against insect infestation.

Fourth, 'spreading of shredded logging residues to improve forest regeneration conditions'. Notably, this method of removing residues left behind by logging from logging sites somewhat differs in domestic and international practice [19]. In the Russian Federation, shredding refers to sawing large logging residues up to 1 m in length. In contrast, in other regions, such as Europe, it refers to shredding using a trailed or self-propelled chipper or mulcher. It is obvious that the method in its international form comes at a significantly higher cost, but it also performs significantly better. Chips quickly decompose, are not initially suitable for pest infestation, and do not impede the growth of the next forest generation. Meter-long logging residues can be infested with insect pests and impede woody growth. Moreover, they do not decompose quickly enough, especially in cryolithic zone forests; this feature makes them a forest combustible material [15].

Fifth, 'stacking and leaving logging residues to decompose at the logging site'. It should be noted that this is the most controversial provision of the above-mentioned Order of the Ministry of Natural Resources and the Environment of the Russian Federation No. 367, which was published simultaneously with this document. This option does not allow for any transport or processing operations with the logging residues. Therefore, it can actually be read as '...or it is allowed to do nothing at all with the logging residues lying on the logging site'. Certainly, given the zero cost of cleaning up logging residues at logging sites, this option is the most appealing to loggers. However, it is also the least suitable for good forest management, as logging operations pose a high fire and phytopathological risk, making forest regeneration more difficult. Nevertheless, this clear-cutting method is relatively common in logging enterprises in remote regions of Russia. Still, it attracts a lot of criticism from forestry division employees, leading to fines 'for not clearing logging areas' and legal proceedings [20]. Nevertheless, suppose this method is prescribed in the statutory document and outlined in the approved process map for operations in the harvesting area. In that case, the logger, not the forestry division, has the legal right to use this method to remove logging residues, despite its inadequacy. Forest residues left in a logging site for decomposition can positively affect the soil. Decomposing, they gradually enrich the soil with organic substances and nutrients. It can improve soil fertility and foster plant growth [21]. In addition, forest residues left in a logging site can protect the soil from erosion, especially on steep slopes. They can prevent the soil from being washed away by water and preserve the soil structure. Dry forest residues in a logging site may increase the risk of forest fires. They serve as a combustible material and can easily ignite, especially in arid conditions. This feature can be a negative aspect for the biosystem and the environment [22].

Sixth, 'hauling logging residues to recycling facilities'. This option is preferable in some cases, particularly for logging in potting soils with high carrying capacity (categories I and II) during the warm season or when concentrating operations at the upper storage site. Logging residues are frequently used to reinforce not only the cutting strips and the main skidding trails but also the driving surface of logging roads. Logging operations use logging roads as temporary transportation routes [23]. Hence, logging residues can be utilised for the entire operation period of logging roads, significantly lowering the cost of constructing such roads.

In the case of short hauling distances, logging residues can be shredded into fuel chips using the previously mentioned trailed or self-propelled chippers and supplied to nearby settlements. However, because the bulk coefficient of wood chips is less than 0.3, transporting them over long distances makes no economic or environmental sense and may even be harmful. During the Soviet era, medium- and large-scale timber farms ran successful 'consumer shops' that recycled larger wood chips, among other things [24].

The aforementioned Order of the Ministry of Natural Resources and Ecology No. 367 also states that 'the said methods of clearing logging sites can be used in combination, if necessary'. Some logging residues, for example, can reinforce the driving surface of skidding trails if necessary, and others can be used to build haul road spurs or for other purposes outside the logging site [25].

3. ESTIMATING STOCKPILES OF LOGGING RESIDUES

Depending on the harvesting method, logging residues may be concentrated in haul roads' upper storage sites. This happens at a storage site during skidding, delimbing, and cross-cutting. This option is less common in the Russian Federation and is associated with Canadian logging technology. This system comprises several machines, including a feller buncher (FB), a grapple skidder, and a processor (delimber-crosscutter). It is also possible to run a single-machine complex, a feller-buncher processor (FBP), but it is not currently common in Russia [26]. This option is the most productive for the machine and process system (aside from FBP). However, it is primarily employed in large and medium-sized forestry enterprises in Siberia and is not very common in Russia. Nonetheless, logging residues are always left on cutting strips, even when trees are skidded. In addition, some crowns fall off when trees are cut down, especially during frosty winters, and must be removed later.

The currently most popular Scandinavian harvesting technology in the Russian Federation is another frequently used option. It is useful when the entire volume of logging residues is still present on the cutting strips. The most popular harvesting option in this technology for machines is a pair of harvesters (feller-delimber-buncher) + forwarders (sorters). In any case, this process can also be completed by a single-machine complex, consisting of either a harvester or a forwarder [27]. However, harvesters are no longer used in the Russian Federation. Moreover, only about 30 forwarders (Ponsse Dual) were purchased before the sanctions war with Russia. Insignificantly prevalent in the Russian Federation is the mechanised (with gasoline-powered saws) Scandinavian logging (for forwarders). However, the cutting strips somewhat account for the entire volume of logging residues in Scandinavian harvesting. When the harvester is operating, a significant portion of the crown may be dropped on the cutting strip skidding trail and later flattened by the forwarder, but not always. In many instances, logging residues are dispersed evenly throughout the entire harvesting area [28]. For example, Figure 2 shows a clear-cut site of mature and overmature pine stands by a harvester + forwarder machine, leaving the seed trees at a logging site in the Irkutsk Region in 2022.

Figure 2. Logging in the Irkutsk Region [28]

The logging site is covered by a continuous carpet of logging residues. Some residues are sufficiently large – trim ends and upper portions of the trunk with a diameter of less than 16 cm, as shown in Figure 2. It should be noted that many multi-forest regions of the Russian Federation, including the Irkutsk Region, Krasnoyarsk Krai, and the Republic of Sakha (Yakutia), regularly leave the upper portions of trunks with a diameter of less than 16 cm on the harvest area in the form of logging residues. These regions share a common characteristic: no wood processing businesses (board factories, pulp and paper mills) use paper wood. Paper wood refers to the upper, more delicate portion of the trunk.

Loggers occasionally leave unclaimed top (paper wood) logs at the loading site, stacking them separately when forwarders are unloaded (Figure 3). This stack is then either burned when there is a fire risk or allowed to decompose [29].

Figure 3. A stack of tree-top trimmings at a loading point in the Republic of Sakha (Yakutia) [28]

However, this ideal concentration of large logging residues on the roadside is the exception rather than the rule. Large logging residues and crown fragments can be found mixed in most of the studied logging sites (Figure 4).

Figure 4. A logging site covered with mixed large (trunk) logging residues and crown portions (Krasnoyarsk Krai) [28]

Table 1. The volume of limbs, stumps, and roots in different tree species [30]

Tree Species	Bark Volume, % of Trunk Volume in the Bark	The Volume of Limbs and Branches, % of Trunk Volume	The Volume of Stumps and Roots, % of Trunk Volume in Whole, Mature Stands	
			Stumps	Stumps and Roots
Pine	10-17	4-10	8-12	18-25
Spruce	7-5	5-12	10-12	25-30
Oak	17-20	6-15	10-12	22-35
Birch	-	3-8	8-10	22-24
Alder	-	5-12	8-10	22-24
Aspen	13-15	5-12	8-10	22-24

According to the literature, the volume of a tree's crown as a percentage of trunk volume is 3-12%. Table 1 provides more precise data. Even if the species composition is the same at each harvesting site, the percentage of crown volume relative to trunk volume will vary to one side or the other. The plantation's age, size, growth class, and density all play a role here [31]. For example, according to literature data, the crown percentage of the most common deciduous trees (birch, aspen) with a trunk diameter of 10-20 cm at breast height is ±15%, and when the trunk diameter increases to 30 cm, the crown percentage can be as much as 3-5%. The data on pine and spruce with the same size trunk is as follows: with a trunk diameter at 10-20 cm of breast height, the crown percentage is ±9%, and with an increasing trunk diameter up to 30 cm, it is 4-5%.

Clear-cutting of mature and overmature stands – previously known as primary forest thinning, final felling, or even reforestation thinning – produces the majority of the logging residues that must be subsequently removed. The diameter of trunks at breast height varies greatly in these conditions. However, there are no discussions concerning the currently popular cutting method of removing only logs 14-16 cm in diameter and leaving the tree-top portion on the logging site. Consequently, large levels of the crown-to-trunk volume percentages can serve as a minimum guide (according to Table 1).

4. MACHINE SYSTEMS AND TECHNOLOGIES TO REMOVE LOGGING RESIDUES

The Canadian harvesting method involves skidding, delimbing, and cross-cutting at the upper storage site. In this case, the majority of the crown, as well as the unclaimed top portions of the tree trunks (Figure 3), remain at the site adjacent to the haul road. Logging residues remain on cutting strips and during subsequent skidding of tree-length logs, particularly in Scandinavian harvesting methods [32]. This process includes wood culls and unclaimed top cuts from the trunk.

As previously stated, logging residues are manually collected after selective felling or clear-cutting, with new growth of the main tree species evenly distributed throughout the area. At the same time, this operation has very low productivity. Grigoreva et al. [28] provide data on the potential productivity for manual removal of logging residues. The researchers analyzed the type of timber to be skidded, the season of logging operations, and the plantation composition (Table 2).

Table 2. Output rates for manual removal of logging residues, ha per man-day (7-hour shift) [33]

Plantations	Skidding			
	Trees		Tree-Length Logs	
	In Winter	In Summer	In Winter	In Summer
Spruce and fir	0.18	0.22	0.2	0.24
Pine	0.30	0.35	0.4	0.45
Deciduous	0.2	0.25	0.25	0.26
Mixed	0.19	0.23	0.23	0.26

The logging case mentioned above is in the Irkutsk Region where pure pine stands mostly grew. A rake picker, a skidding tractor with mounted technological equipment, works best when harvesting logging residues evenly scattered over the site after clear-cutting without new growth preservation (Figure 5).

Figure 5. A rake picker PSG-2.4/PSG-2.9 based on TDT-55A crawler tractor

Grigoreva et al. [33] provide the following data for the potential productivity of removing logging residues with a rake picker, depending on forest yield per hectare and logging site size (Table 3).

Table 3. Output rates for removal of logging residues with a rake picker, ha per shift (7-hour shift) [33]

Length of Rut, m	Forest Yield per 1 ha, m^3		
	Less Than 80	80-120	121 or More
100	3.0	3.0	2.9
200	3.4	3.4	3.4
300	3.6	3.6	3.5
400	3.7	3.7	3.6
500	3.8	3.7	3.6

The comparison of Tables 2 and 3 shows that the productivity of machine cleaning of logging residues from logging sites is unaffected by plantation composition, the type of wood being skidded, or the harvesting season. Second, the lowest output rate for machine cleaning (for the most unfavourable conditions) is more than six times higher than the highest output rate for manual logging (for the most favourable conditions).

In most cases, forestry teams are small. Typically, there are five to six people. These people are highly skilled and expensive operators who cannot be employed to manually harvest logging residues. It is not always possible to recruit harvesting crews from the local population. Even when offered relatively high wages for this physically demanding work, it is difficult to hire a cleaning crew for various reasons, most of which are socio-demographic.

It is currently very challenging to find a tractor that can serve as the base for the rake picker due to the nearly complete eradication of the domestic forestry machine industry [33]. The wheeled forwarders commonly used by Russian forestry companies are unsuitable for this purpose. In addition, almost no tracked machines can deliver the necessary traction force.

The principle of raking, for example, hay (Figure 6), is also used in agriculture with tractor-mounted machinery. However, there are no stumps, stones, or other impediments on cultivated agricultural fields. PSG-2.4/PSG-2.9 or LT-161 forestry pickers have each tooth mounted on an individual hinge, allowing the tooth to go up when encountering such an obstacle and then down again after passing it.

Figure 6. Hay rake picker

Before starting the rake picker, the machine cleans the felling area by placing a marker on the felling area that is clearly visible to the operator. At the same time, the machine forms the axes by the swath picker. Picker strokes are perpendicular to the logging swath axes and usually cross the swath guides (Figure 7) [28]. At the beginning of the swath, the picker lowers the rake unit and drives to the first shaft axis, at which point it raises the rake unit, leaving behind the harvested residues. The rake unit is lowered once more, and the loader advances to the second shaft axis, and so on. When the loader reaches the end of the swath, it shifts to the width of the rake and drives away in the opposite direction. The cycle of swath collection is repeated.

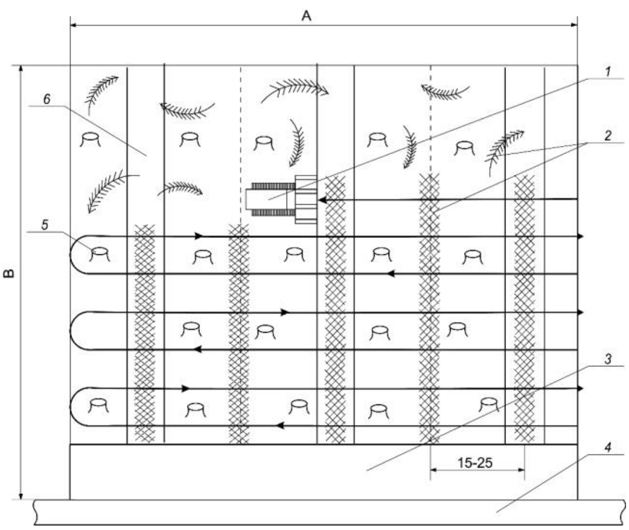

Figure 7. A diagram of clearing logging sites from logging residues with a rake picker [28]: 1 – delimbing rake; 2 – logging residues; 3 – safety zone; 4 – haul road spur; 5 – logging site; 6 – cutting strip skidding trail

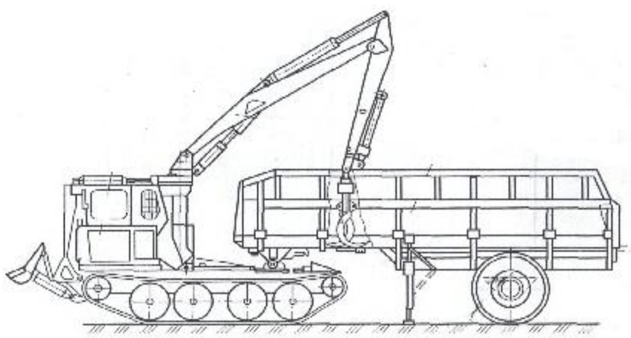

Figure 8. A manipulator picker for logging residues

Suppose the plan is to collect and remove the woody debris for later use. In that case, a manipulator picker is equipped with a logging residue hopper trailed technological equipment attached to a chokerless skidder. The manipulator picker begins working once the rake picker finishes working or moves to a safe distance (Figure 8).

In other words, the above technology employs a two-machine complex to collect and transport logging residues to the haul road spur. Grigoreva [34] proposed a single-machine complex for collecting and transporting logging residues to the haul road spur (Figure 9). It is a basic tractor with trailed technological equipment – a roller with spikes – and a body for logging residues attached to it. The roller's heavyweight catches large logging residues against the spikes on its outer body as it moves over the logging site. The logging residues caught on the spikes reach the shaped slots on the edge of the body as the drum rotates, allowing the spikes to pass through while removing the logging residues caught on the spikes. After unhooking the roller and loading the body, the machine can move to the storage location for the collected cargo. This technical solution eliminates the need for a powerful caterpillar tractor, as the rolling resistance of the roller is considerably less than the drag resistance of the logging residues collected by the rake.

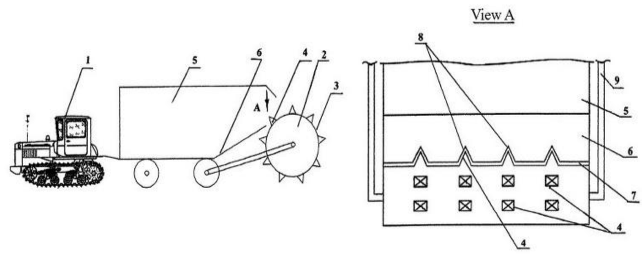

Figure 9. Single-machine logging residue removal system [34]: 1 – basic tractor; 2 – roller; 3 – the working surface of the roller; 4 – sharp spikes; 5 – body; 6 – a sloping wall of the body; 7 – upper edge of the sloping wall of the body; 8 – shaped slots; 9 – brackets securing the roller to the tractor

As previously stated, large logging residues pose the greatest fire and phytopotential hazards. In turn, small logging residues, which the machine in Figure 9 cannot collect, pose no danger. On the contrary, they will quickly decompose and fertilise the soil layer at the logging site.

Logging residues can be deposited on skidding trails in poor ground conditions or in piles on the cutting strip on the side of the skidding trail. It is possible in good ground conditions during harvesting using the most popular harvester+forwarder machine system currently used in Russia and worldwide. In the latter case, logging residues can be collected efficiently because they are concentrated in piles. Their volume correlates with the number and species of trees the harvester can handle from a single processing stand. In addition, foreign countries collect logging residues using special machines in Scandinavian machine harvesting technology. It bundles them into sheaves and saws these sheaves to the same length (Figure 10) [35].

A common forwarder will then gather the resulting sheaves of logging residues and deliver them to the loading location. These sheaves are then transported by timber trucks to their final destination (usually a boiler house, where they are crushed into fuel chips and burned to generate thermal energy). In the Russian Federation, Luzales LLC has operating experience with such machines in the Republic of Komi. However, even in bundled logging residues, the solid-volume/stacked-volume ratio is low. This feature makes this option unprofitable for long-distance hauling, which, as previously stated, is common in Siberia and the Far East.

Figure 10. A machine for harvesting and bundling logging residues on a cutting strip

Each of the studied methods has a different impact on the environment. For example, methods based on the decomposition of forest residues can improve the condition of the soil and prevent fires. However, they can also increase the risk of soil and water pollution. Another important aspect is the economic efficiency of each method. It is necessary to consider the costs of the introduction and use of technology, as well as potential benefits, such as additional processing of forest residues into biofuels or other products. The effect of each method on the environment also requires a comprehensive analysis. Some methods contribute to the decomposition of forest residues while improving the soil and reducing fire resistance. Others can lead to potential problems with soil pollution and damage ecosystems.

Further research into forest residue disposal is a complex field for researchers and practitioners, having both challenges and prospects. One of the main tasks will be to assess the sustainability of various residue disposal methods in the context of their impact on ecosystems and the environment. A deeper understanding of how the methods impact biodiversity, soil conditions, and environmental pollution levels will remain an urgent area of research. In addition, research should pay attention to the economic efficiency of various methods and their cost to provide an informed choice for forest enterprises and management bodies. The development of new technologies and innovations in this area opens up prospects for more efficient and sustainable forest management. Given the diversity of geographical and climatic conditions, it is also necessary to investigate the adaptation of methods in different regions. In this case, a wider scale of application will be possible. Finally, research on the development of recommendations for policy and regulation in this area can contribute to more sustainable use of forest resources and conservation of the natural environment.

5. CONCLUSIONS

The continuous slash-and-burn method, instead of burning logging residues in piles or swaths, is sufficiently effective for many countries worldwide. However, it is possible to use it only during fire-prone periods. The method's main disadvantage is the use of paraffin, which cannot be poured over the entire logging site. However, an artificial grass fire does not cause severe thermal damage to the soil; the felling residues are only charred, not completely burned. Subsequently, they decompose much faster, fertilising the soil, becoming non-fire hazardous, and of no interest to insect pests.

In addition, Russia, as the forest owner, sells standing timber to forest users without regard for the crown. Consequently, the stock of crown wood can be considered an inherently free resource, which is imperative to use effectively. Notably, most modern logging companies harvest wood with various harvesting machines as opposed to gasoline-powered saws. This approach improves logging residue management efficiency. Furthermore, as mentioned above, the manual collection of logging residues on large stumps allows for larger piles, reducing the frequency of their carrying. However, the logging residues from these piles are difficult to collect and transport to a recycling centre, such as an upper storage site. Therefore, applying and developing new transport methods is a promising study area.

To summarise, logging residues are a free raw material that can be processed further, primarily into wood biofuel. Energy efficiency is the criterion for the effectiveness (expediency) of logging residue collection and processing into wood biofuel, as well as its transportation to the place of consumption. Therefore, the energy needed to collect, process, and transport the logging residues must be less than their energy intensity.

ACKNOWLEDGMENT

The study was carried out within the confines of the Scientific School Advances in Lumber Industry and Forestry.

The study was funded by Krasnoyarsk Regional Fund of Science and Krasresurs 24 LLC within the framework of scientific project (Grant No.: 2022052708731); the Russian Science Foundation (Grant No.: 23-16-00092). https://rscf.ru/project/23-16-00092/

REFERENCES

[1] Ghaffariyan, M.R., Dupuis, E. (2021). Analysing the impact of harvesting methods on the number of harvesting residues: An Australian case study. Forests, 12(9): 1212. https://doi.org/10.3390/f12091212

[2] Ghaffariyan, M.R. (2023). Short review of collecting technologies and methods in forest harvesting residue recovery. Silva Balcanica, 24(1): 55-68. https://doi.org/10.3897/silvabalcanica.24.e97620

[3] Wall, A., Hytönen, J. (2011). The long-term effects of logging residue removal on forest floor nutrient capital, foliar chemistry and growth of a Norway spruce stand. Biomass and Bioenergy, 35(8): 3328-3334. https://doi.org/10.1016/j.biombioe.2010.08.063

[4] Mokhirev, A., Zyryanov, M., Ryabova, T., Vititnev, A. (2019). Evaluation of possibility of obtaining woodchips from wood residues. Journal of Applied Engineering Science, 17(2): 140-143. https://doi.org/10.5937/jaes17-20453

[5] da Rocha Miranda, J., da Silva, R.G., Juvanhol, R.S. (2022). Forest fire action on vegetation from the perspective of trend analysis in future climate change

scenarios for a Brazilian savanna region. Ecological Engineering, 175: 106488. https://doi.org/10.1016/j.ecoleng.2021.106488

[6] Grigoreva, O.I., Lorenz, A.S., Grigorev, I.V. (2023). Occupational health and safety when operating a needle-filtering unit for extinguishing forest fires. Safety and Labour Protection in Logging and Wood-Processing Industries, 1: 37-43. https://elibrary.ru/item.asp?id=50384762.

[7] Grigoreva, O.I., Runova, E.M., Tikhonov, E.A., Storodubtseva, T.N., Druzyanova, V.P., Gerts, E.F., Garus, I.A., Grigorev, I.V. (2022). Dynamics of the taxation characteristics of forest stands in the north-west of Russia. Polish Journal of Environmental Studies, 31(5): 4107-4115. https://doi.org/10.15244/pjoes/147588

[8] Sire, L., Yáñez, P.S., Cai, W., Bézier, A., Courtial, B., Cours, J., Fontaneto, D., Larrieu, L., Bouget, C., Thorn, S., Müller, J., Yu, D.W., Monaghan, M.T., Herniou, E.A., Lopez-Vaamonde, C. (2022). Climate-induced forest dieback drives compositional changes in insect communities that are more pronounced for rare species. Communications Biology, 5(1): 57. https://doi.org/10.1038/s42003-021-02968-4

[9] Grigoreva, O.I., Grigorev, I.V., Grinko, O.I., Ivanov, V.A., Kalita, O.N. (2022). Analysis of reforestation results in conditions of Baltic-Belozersky taiga region. Systems. Methods. Technologies, 1(53): 86-92.

[10] Sk, P.G.P., Debnath, S., Maitra, S. (2020). Mulching: Materials, advantages and crop production. In Protected Cultivation and Smart Agriculture. New Delhi Publishers, New Delhi, pp. 55-66. https://doi.org/10.30954/NDP-PCSA.2020.6

[11] Rudov, S.E., Grigorev, I.V. (2021). Ways to improve the efficiency of machine systems for assortment timber harvesting. In Increasing the efficiency of the forestry complex. Proceedings of the Seventh All-Russian National Scientific and Practical Conference with International Participation, Petrozavodsk, pp. 168-169. https://elibrary.ru/item.asp?id=45618615.

[12] Grigorev, I., Burgonutdinov, A., Makuev, V., Tikhonov, E., Shvetsova, V., Timokhova, O., Revyako, S., Dmitrieva, N. (2022). The theoretical modelling of the dynamic compaction process of forest soil. Mathematical Biosciences and Engineering, 19(3): 2935-2949. https://doi.org/10.3934/mbe.2022135

[13] Marra, E., Laschi, A., Fabiano, F., Foderi, C., Neri, F., Mastrolonardo, G., Nordfjell, T., Marchi, E. (2022). Impacts of wood extraction on soil: Assessing rutting and soil compaction caused by skidding and forwarding by means of traditional and innovative methods. European Journal of Forest Research, 141: 71-86. https://doi.org/10.1007/s10342-021-01420-w

[14] Grigoreva, O.I., Runova, E.M., Storodubtseva, T.N., Urazova, A.F., Voronova, A.M., Ivanov, V., Shvetsova, V.V., Grigorev, I.V. (2022). Comparative analysis of thinning techniques in Garchinsky forest. Mathematical Modelling of Engineering Problems, 9(2): 762-770. http://dx.doi.org/10.18280/mmep.090324

[15] Grigorev, I.V., Gazizov, A.M., Grigoreva, O.I. (2016). New technological processes for logging operations. Bulletin of Bashkir State Agrarian University, 2(38): 97-102. https://elibrary.ru/item.asp?id=26320468.

[16] Dymov, A.A., Startsev, V.V., Gorbach, N.M., Severgina, D.A., Kutyavin, I.N., Osipov, A.F., Dubrovsky, Y.A. (2022). Middle taiga, Komi republic. Eurasian Soil Science, 55(11): 1633-1646. https://doi.org/10.1134/S1064229322110023

[17] Pingree, M.R., Kobziar, L.N. (2019). The myth of the biological threshold: A review of biological responses to soil heating associated with wildland fire. Forest Ecology and Management, 432: 1022-1029. https://doi.org/10.1016/j.foreco.2018.10.032

[18] Mamaeva, O.O., Isaeva, E.V. (2021). Use of post-extraction fir wood greenery residues by the bioconversion method with the production of feed additives. Forests, 12(3): 272. https://doi.org/10.3390/f12030272

[19] Palviainen, M., Finér, L., Kurka, A.M., Mannerkoski, H., Piirainen, S., Starr, M. (2004). Decomposition and nutrient release from logging residues after clear-cutting of mixed boreal forest. Plant and Soil, 263: 53-67. https://doi.org/10.1023/B:PLSO.0000047718.34805.fb

[20] Zumr, V., Remeš, J., Pulkrab, K. (2021). How to increase biodiversity of saproxylic beetles in commercial stands through integrated forest management in central Europe. Forests, 12(6): 814. https://doi.org/10.3390/f12060814

[21] Ojanen, P., Mäkiranta, P., Penttilä, T., Minkkinen, K. (2017). Do logging residue piles trigger extra decomposition of soil organic matter? Forest Ecology and Management, 405: 367-380. https://doi.org/10.1016/j.foreco.2017.09.055

[22] Prats, S.A., González-Pelayo, Ó., Silva, F.C., Bokhorst, K.J., Baartman, J.E., Keizer, J.J. (2019). Post-fire soil erosion mitigation at the scale of swales using forest logging residues at a reduced application rate. Earth Surface Processes and Landforms, 44(14): 2837-2848. https://doi.org/10.1002/esp.4711

[23] Routa, J., Asikainen, A., Björheden, R., Laitila, J., Röoser, D. (2016). Forest energy procurement: State of the art in Finland and Sweden. In Advances in Bioenergy: The Sustainability Challenge, pp. 273-283. https://doi.org/10.1002/9781118957844.ch17

[24] Grigorev, I.V., Grigoreva, O.I., Nikiforova, A.I., Glukhovsky, V.M. (2016). Prospective directions of development of technological processes of logging works. Proceedings of BSTU. No. 2. Forestry and Woodworking Industry, 2(184): 109-116. https://cyberleninka.ru/article/n/perspektivnye-napravleniya-razvitiya-tehnologicheskih-protsessov-lesosechnyh-rabot.

[25] Grigorev, I.V., Nikiforova, A.I., Grigoreva, O.I. (2015). Comparison of single-machine complexes for assortment logging. Actual Directions of Scientific Research of the XXI Century: Theory and Practice, 3(9-2): 125-128. https://elibrary.ru/item.asp?id=25116325.

[26] Kunickaya, O., Pomiguev, A., Kruchinin, I., Storodubtseva, T., Voronova, A., Levushkin, D., Borisov, V., Ivanov, V. (2022). Analysis of modern wood processing techniques in timber terminals. Central European Forestry Journal, 68(1): 51-59. https://doi.org/10.2478/forj-2021-0017

[27] Häggström, C., Lindroos, O. (2016). Human, technology, organisation and environment – A human factors perspective on performance in forest harvesting. International Journal of Forest Engineering, 27(2): 67-78. https://doi.org/10.1080/14942119.2016.1170495

[28] Grigoreva, O.I., Makuev, V.A., Baryshnikova, E.V.,

Burmistrova, O.N., Shvetsova, V.V., Grigorev, I.V., Ivanov, V.A. (2022). Prospects of import substitution systems for artificial reforestation machines. Systems. Methods. Technologies, 3(55): 78-84.

[29] Laitila, J., Asikainen, A., Ranta, T. (2016). Cost analysis of transporting forest chips and forest industry by-products with large truck trailers in Finland. Biomass and Bioenergy, 90: 252-261. https://doi.org/10.1016/j.biombioe.2016.04.011

[30] Shirnin, Y.A., Grigorev, I.V., Nikiforova, A.I., Nikiforov, A.A. (2012). Forest resource management: Textbook for undergraduate students of the 250400.62-degree programme Technology for Forestry and Wood Processing majoring in Forest Engineering. Volga Region State Technological University, Yoshkar-Ola.

[31] Colón, S.M., Lugo, A.E. (2006). Recovery of a subtropical dry forest after abandonment of different land uses 1. Biotropica: The Journal of Biology and Conservation, 38(3): 354-364. https://doi.org/10.1111/j.1744-7429.2006.00159.x

[32] Staaf, A., Wiksten, N.A. (2013). Tree harvesting techniques (Vol. 15). Springer Science & Business Media.

[33] Grigoreva, O.I., Davtyan, A.B., Grinko, O.I. (2020). Prospects for import substitution in the production of forestry and forest fire-fighting machines in Russia. In Forest Exploitation and Integrated Wood Use. Collection of articles of the All-Russian Scientific and Practical Conference, Krasnoyarsk, pp. 66-69. https://elibrary.ru/item.asp?id=42974643.

[34] Grigoreva, O.I. (2014). New machine for logging site cleaning. Actual directions of Scientific Research of XXI Century: Theory and Practice, 2(5-3): 96-99. https://naukaru.ru/ru/nauka/article/4370/view.

[35] Grigorev, I.V., Redkin, A.K., Valyazhonkov, V.D., Matrosov, A.V. (2010). Technology and equipment for forestry industries. Technology and machinery of forestry works: Textbook. LTA Publishing House, Saint-Petersburg.