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RESEARCH ARTICLE

Suitable forestry machines for mechanical fuel load reduction and salvage recovery: a short review

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Abstract

Forest fires are one of the most severe incidents that can destroy large areas of forest lands and cause substantial damages to the nearby residential areas and farmlands. Human efforts to reduce the likelihood of starting forest fires include prescribed burning, mechanical fuel load reduction and livestock grazing. Following natural disasters in forest areas, a salvage recovery operation is usually conducted that may cause some environmental impacts. This article aimed to review the literatures to provide a summary of different types of machines and working methods that have been studied in different countries. The review results showed that the most common method for mechanical fuel load reduction was mechanised cut-to-length using a harvester and a forwarder. This method has been widely applied in Canada, USA, Europe, and Oceania. In some countries (e.g. Australia and USA) the whole tree method is also applied for mechanical fuel load reduction. This method was often conducted using feller-bunchers, grapple skidders and chippers/grinders. The majority of mechanical fuel load reduction projects produced the extra fibre which could be used for bioenergy purposes. The number of salvage recovery studies was limited compared with studies on mechanical fuel load reduction. Salvage recovery operations applied a cut-to-length and whole tree harvesting methods. Windthrown trees were extracted to the roadside using heavy size forwarders or grapple skidders in flat/moderate terrains while tower yarders were applied in steep terrains. Detailed information on work productivity is described in this article which can be of use to the academic and industrial users.

Keywords

Forest machine, Harvesting, Mechanical fuel load reduction, Salvage recovery, Productivity

Introduction

Forest fires are one of the most severe incidents that can destroy large areas of forest lands and cause substantial damages to the nearby residential areas and farmlands. Human efforts to reduce the likelihood of starting forest fires include prescribed burning, mechanical fuel load reduction and livestock grazing (Royal commission, 2020). One of the main post-harvest activities is salvage recovery that includes harvesting the trees which have been killed by the wildfire (or windstorms) to recover sufficient values before they degrade (Fitzgerald et al. 2018 cited in Jenkin (2020); Cadei et al. 2020). However, salvage harvesting can cause some environmental impacts including negative impacts on biodiversity, tree species composition at the stand and landscape level, and water catchment integrity. Understanding these impacts and considering them in planning is essential for a successful ecosystem recovery and sustainable natural resource management (Lindenmayer, 2006; Lindenmayer and Ough, 2006;

Lindenmayer et al. 2003). Cadei et al. (2020) and Kärhä et al. (2018) indicated that mechanized harvesting systems are the most appropriate ones to use for salvage harvesting as they are more productive systems which provide adequate safety standards for the machine operators. In salvage recovery operations, the terrain might be steep and working conditions are not normal as with conventional harvesting. Previous research in Finland showed the cutting cost can be about 35-64% higher than clear cutting normal standing trees while the harvesting cost was 10-30% higher than clear cutting normal standing trees (Kärhä et al. (2018) cited in Cadei et al. (2020)).

Mechanical fuel load reduction is one of the fire risk mitigation methods that deals with collecting and removal of a proportion of available fuel (including available biomass, harvesting residues (Li et al. 2022), understory etc.) in forest stands. The goal of this method is to reduce the size, likelihood and severity of bushfires (Ximenes et al. 2017). According to Acuna et al. (2018) and Ximenes et al. (2017) for mechanical fuel load reduction there are some factors to consider when selecting suitable harvesting equipment and methods which include tree size, terrain conditions and the use of biomass treatment (recovered to use or treated on the site to reduce fire risk). Acuna et al. (2018) suggested using small and agile machines to minimise the impacts on the soils and remaining stands. To harvest the stands with diameter larger than 8-10 cm it would be better to apply mechanised feller-bunchers to fell and bunch the trees that can be either chipped or grinded for further use for bioenergy or leaving them on the site to diminish fire risk. Stands with trees smaller than 8-10 cm would be ideal to be harvested using farm technologies such as forage harvesters, mowers and grinders (Lorensi do Canto et al. 2011 cited in Acuna et al. 2018). Managing natural threats (including forest fires and windstorms) often requires the application of heavy harvesting machines. Thus, this article aimed to review the literatures to provide a summary of different types of machines and harvesting operations methods applied in different countries.

Methods

To find relevant reports and articles on the topic of this research, the following keywords were used for the search including Forest, Harvesting machines, Salvage, Forest fire and Fuel load reduction. The electronic databases such as Google Scholar, Scopus and Web of Science, Research Gate and Academia were used to conduct the web-based search. After primary screening of the topics and contents, a total of 17 relevant reports were selected for review. The results were classified based on the region/countries with a brief description of the research area (stand and terrain conditions), applied machines and their working method in fuel reduction and salvage recovery plus work productivity records where available. A summary of the key results (including harvesting operations methods and machines) was prepared to highlight the available knowledge in a glance.

There are three main harvesting methods including whole tree (WT), tree length (TL) and cut-to-lenght (CTL) (Stampfer, 2006). The whole tree method refers to an approach where trees are felled manually or mechanically then often are topped prior to being extracted as a whole tree (including tree crown) to the roadside for further processing. Tree length is described as an operation where trees are felled, topped and debranched to long lengths then the tree lengths are extracted to the roadside/landing. In cut-to-length harvesting, trees are felled and processed to short logs at the stump then the logs are extracted to the roadside (Lundbäck et al. 2021; Kellogg et al. 1993). From a system viewpoint, forest operations can be conducted using manual harvesting, semi-mechanised or fully mechanised harvesting systems (Stampfer, 2006).

From a ground slope perspective, harvesting operations can be carried out by ground-based systems (on the terrain with slope less than 55%) or cable yarding systems (applied on terrains steeper than 55%). Common machines in ground-based harvesting are feller-bunchers, harvester-processors, skidders/tractors and forwarders (Conway, 1982). Feller-buncher is a machine equipped with a boom and felling head that can fell and bunch the trees. The harvester processor is a machine that can fell the trees, delimb, top, crosscut to short logs. A skidder is a four-wheeled-drive machine with articulated steering equipped with grapple or cable winch to extract the trees/logs by lifting one end of the trees/logs. A forwarder is a rubber-tired machine equipped with a loading bunk and grapple which is usually used to pick up the short/long logs (in cut-to-length operations) and extract them to the roadside/landing (Kellogg et al. 1992). A cable harvesting system consists of a tower (head-spar), set of winch drums, source of power to winch logs, whole trees or part of trees (e.g. logs) partially or fully suspended for uphill or downhill extraction (Tiernan et al. 2002).

Work productivity is a terminology of forest operations research that has been used in this review article. Heinimiann (2021) published a comprehensive educational manuscript on operational productivity studies in forestry where he referred to Griliches (1998) who defined work productivity as a ratio of some measure of output to some measure of input uses. Simple work studies (e.g. time study such as plot level, shift level and work cycle) are often used to measure the mass output and time input to determine the productivity of a harvesting machine. Work productivity of harvesting machines can be impacted by various factors including technology type, environmental conditions, stand characteristics, operator skills and working methods (Magagnotti et al. 2012).

Results

Europe

Italy

The Viva storm occurred in 2018 in Italy and Cadei et al. (2020) assessed the forwarder's productivity to recover timber from three study sites within windthrown forests in the Italian Alps. The damaged area varied from 40% to 100%. Slopes ranged from 17% to 33% and the stands composed of species including *Abies alba, Picea abies, Larix decidua* and broad leaves including *Fagus sylvatica*, *Acer pseudoplatanus* and *Betula pendula.* Windthrown trees were firstly processed to the logs by harvester-processors then the logs were extracted using medium and heavy size forwarders to the roadside. Machine models included John Deere 1210 E (engine power of 182 HP), Ecolog 574 B (engine power of 173 HP) and a heavy forwarder Ponsse Buffalo (engine power of 282 HP). Loading capacity varied from 13 to 15 tonnes. Forwarding distance varied from 250 m to 500 m and average log volume ranged from 0.25 m^3 to 0.35 m^3. Time study results predicted an average productivity of 14.4 to 20.5 cubic meters per productive machine hour, including delays smaller than 15 minutes (m^3/PMH_{15}) for the medium size forwarders. The heavy forwarder (Ponsse Buffalo) yielded larger predicted productivity of 18.8 to 23.0 m^3/PMH_{15}. Statistical analysis confirmed that increasing forwarding distance and ground slope diminished the productivity while the load volume, number of logs and maximum machine inclination during loading were positively impacting the forwarder's productivity. Italian scholars mentioned that forwarders' productivity (especially for heavy forwarders) was lower in the salvage harvesting compared to normal operation which might be due to non-ordinary situations including difficult terrain and irregular pattern of tree felling and load accumulation (Cadei et al. 2020). Another case study was carried out on windthrown stands in mixed stands of fir (*Abies alba* L.), spruce (*Picea abies* Karst) and beech (*Fagus sylvatica* L.) located in the Eastern Italian Alps (province of Udine). The study sites were steep where ground-based harvesting systems could not operate safely. Spinelli et al. (2023) reported that a Valentini V600/M3/1000 trailer-mounted tower yarder (equipped with SEIK Skytiger ST 30 carriage) was applied to harvest the windthrown stands. The working team included three people. Two chain saw operators topped the windthrown trees and a choker setter connected the chokers to the logs and a machine operator at landing to release the choker with a remote radio control. The machine operator also ran a processor (Konrad Woody 61H) to cut the tree lengths into short logs. In the study area, yarding distance averaged at 200 m and merchantable load size per each turn varied 1.2 to 4.5 m^3. Spinelli et al. (2023) examined three methods of extraction of logs by carriage including horizontal double-hitch (both ends of the log connected by chokers to carriage), single-hitch (one end of the log connected to the carriage) and double- hitch mode (two logs connected to each choker). These methods did not significantly impact the productivity of the yarder. Average productivity varied from 18.2 to 24.5 m^3 per free delay productive scheduled hour m^3/PSH$_0$. A greater number of pieces per turn were extracted via the double-hitch method than single-hitch or horizontal double-hitch. The horizontal double-hitch method was found to be economical only under yarding distances significantly shorter than average distance (Spinelli et al. 2023).

North America

Canada

There have been extensive wildfires in British Columbia in recent years that have encouraged governmental authorities to initiate projects to thin the stands where additional timber can be used as biomass source (Dyson and Hvenegaard, 2021). Harvesters and forwarders are typical machines used in thinning operations. The case study conducted by FPInnovations consisted of 30.9 ha covered by conifer, deciduous, Douglas-Fir (*Pseudotsuga menziesii*), Balsam (*Abies balsamea*), Spruce (*Picea sp.*), Lodgepole pine (*Pinus contorta*). DBH varied from 22 to 43 cm. The terrain was flat. All trees with DBH>40 cm were retained, and the rest of the stand was harvested using an Ecolog 550D harvester and Ponsse Buffalo King forwarder (Figure 1). Conifer stems up to 3 m height were manually pruned. Branches were manually fed into a portable chipper to disperse on the floor. A grinder at the roadside processed the biomass logs into hog fuel. The study yielded both sawlog/pellet logs and biomass materials. Harvester productivity for sawlog/pellet logs was 16.6 m^3/PMH and 30.1 m^3/PMH respectively. Forwarder productivity averaged at 19.8 m^3/PMH for sawlog/pellet logs while in the case of biomass recovery the productivity averaged at a lower rate of 10.7 m^3/PMH (this might be due to the higher piece volume and load volume per

Fig. 1. Harvester and forwarder application in thinning to reduce fire risk in Canada (Dyson and Hvenegaard, 2021)

each turn resulting in shorter loading time in sawlog/pellet logs recovery compared with biomass recovery) (Dyson and Hvenegaard, 2021).

USA

According to a report by Nakamura (1996) drought, insect attack and suppression of wildfires created dense forest stands in California. Considering the growth of the biomass market, harvesting small trees and shrubs using feller-bunchers equipped with shears was an effective method. This method reduced the fuel and fire hazard and created extra fiber as a by-product. Small trees were cut and bunched as whole trees could then be extracted to the roadside by a forwarder to be chipped for biomass purposes.

Larson et al. (2000) evaluated the harvesting costs for three harvesting systems applied in biomass recovery (in small trees with DBH less than 40 cm) to reduce fire risk in Arizona. The study area consisted of three types of *Pinus ponderosa*. Harvesting methods included whole tree harvesting (fully mechanized) and cut-to-length (two types including conventional and manual operations). The whole tree method was applied using a combination of a tracked feller buncher, two grapple skidders, a delimber and a loader to harvest trees with DBH larger than 12.7 cm. Trees with DBH less than 12.7 cm were manually felled, scattered and debranched.

Manual cut-to-length was operated using a chainsaw operator who felled the large trees then processed them into short logs that were then extracted to the roadside by forwarders. Very small and non-merchantable trees were also cut, debranched and scattered. A conventional cutto-length method was employed using a harvester and forwarder that harvested trees with DBH larger than 12.7 cm. Larson et al. (2000) reported that whole tree harvesting was the most cost-effective alternative which was mainly because of higher work productivity (due to the faster work process which consumed a shorter time). American scholars emphasized that in addition to the costs of operations it is required to analyze the market opportunities for thinned materials produced in their trials. The markets included firewood and ethanol. The financial analysis confirmed that not all study alternatives were economical for either solid firewood or ethanol.

Rummer et al. (2003) indicated that biomass materials from thinning (for fuel reduction purposes) including tops, lips and saplings from thinning, could be used for co-generation of electricity while clean chips produced from wood stems could be used as a source for pulp, MDF or particleboard production. Rummer et al. (2003) mentioned that small trees and harvesting residues might be costly to recover; however, any recovery could be beneficial for mechanical fuel load reduction. The following functions were presented (Figure 2) for harvesting operations dedicated for mechanical fuel load reduction in the USA. They also referred to the model that Fight et al. (2003) developed which could predict the cost of mechanical fuel reduction based on variables such as extraction distance, tree volume, harvesting volume per ha, type of harvesting system and unit size.

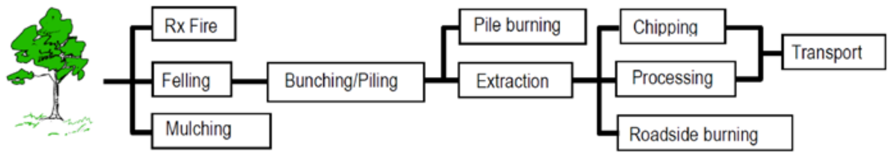

Fig. 2. Operation types for mechanical fuel load reduction (Rummer et al. 2003)

Fig. 3. Bundled and loose biomass collected from the sites in the USA (photo by Dalia Abbas) (Artosi et al. 2008)

Artosi et al. (2008) studied mechanical fuel reduction in Superior National Forest which had fuel load included, dense understory vegetation and standing and down dead materials that created risk of bushfires. The sites were composed of spruce (*Picea abies*), balsam (*Abies balsamea*), and white pine (*Pinus strobus*). The prescription was to remove small trees (DBH<5cm) and dead materials. The main harvesting system was a combination of fell/ process (Ponsse EH-25 biomass harvest head on a harvester), extraction (using a conventional forwarder (Figure 3)), grinding (using a self-loading grinder) and transportation (using a full chip van). A dual harvester/ forwarder was also applied. When biomass materials were bundled or there was a roundwood production, conventional log trucks were used to deliver the products to the destination (transport distance was restricted to 180 km to make biomass recovery economically viable).

Stephens et al. (2012) mentioned mechanical fuel reduction programs do not completely remove the risk of fire however they can help with reducing the costs and liability in some regions. They suggested using a rotary masticator mounted on an excavator (Figure 4) could be useful to reduce the fuel load. This was tested in mixed-conifer forests in California. Becker and Keffe (2020) reported that small excavators with a horizontal shaft masticator head (Figure 5) were used in mechanical fuel reduction treatments in the western United States. Using LiDAR could assist the managers

Fig. 4. Rotary masticator operating in mixed forests in California (Stephens et al. 2012)

Fig. 5. Mini-excavator for mechanical mastication treatment in the USA (Becker and Keffe, 2020)

to predict the fuel load after mastication to assess the impact of the treatments for mechanical fuel load reduction.

Page-Dumroese (2017) described four methods that could be used to pile the excessive harvesting residues and burn them to produce biochar. They indicated that burning large numbers of piles could cause long term damages to the soil. The slash piles could be created by hand, bulldozer, excavator (Figure 6) and grapple/log loader. Piling by hand could be used for small size woods to build loose piles. Bulldozers can push the piles and ride over them to densify the piles. Log loaders and grapple loaders create dense piles too, but they can pick up the harvesting residues to pile them which can create cleaner piles with less soil contaminants compared with the bulldozers.

Conrad IV (2023) studied the productivity and costs of post-Tornado salvage harvesting in the USA. A powerful Tornado occurred in South Carolina in April of 2020 which uprooted loblolly pine (*Pinus Taeda* L.) stands. The terrain was flat. The study area consisted of small tree size (<30cm end diameter) and large size stands (>30 cm end-diameter) which were harvested using a Tigercat 720G feller-buncher, a John Deere 748L-II grapple skidder, a Tigercat T234 tracked loader and a Morbark 40/36 drum chipper. Feller buncher productivity varied from 1.2 to 1.7 stems per minute

Fig. 6. Excavator building forest residue piles (photo by J. G. Archuleta.) in the USA (Page-Dumroese (2017)

(the value in green tonnes per hour was not reported). The results showed a low productivity of the grapple skidder (averaged at 13.3 green tonnes per PMH) in small size tree stands. Skidder productivity increased to a value of 24.0 green tonnes per PMH in a study area with larger tree size. The chipping operation was very efficient with an average productivity of 51 to 72 green tonnes per PMH.

Oceania

Australia

There have been some doubts on the impact of timber harvesting and forest management on the severity and extent of the bushfires in south-eastern Australia. Lindenmayer et al. (2020) indicated that harvesting operations and forestry activities made the bushfire worse and timber harvesting improved the fires' severity and frequency; however, Keenan et al. (2021) analyzed the burnt area during 2019/20 and found no evidence that timber harvesting has increased the severity of the bushfires. Keenan et al. (2021) stated that the main factors causing extreme bushfires were well-below average rainfall, extreme weather, and local topography.

Selective harvesting is applied in some parts of the native forests in Southeast Queensland in Australia. Felling is conducted either manually using chainsaws or mechanically using small harvester processors. Extraction is often carried out using grapple skidders (Pachas, 2023). Lewis et al. (2021) reported that the selective harvesting activity can remove 17% to 37% of live tree basal area that can impact the soil and vegetation attributes. Research results showed that applying selective harvesting increased the bare-ground cover and quantity of harvesting residues per ha. However, selective harvesting decreased the height of understory vegetation (Lewis et al. 2021). Schirmer et al. (2018) reported that according to the views of participants in their social survey, mechanical fuel load reduction might be more perceived and accepted in small-scale areas especially located near built infrastructures or plantations and in areas that it was not feasible to apply bushfire risk mitigation strategies. One of the

Fig, 7. A harvester applied in mechanical fuel load reduction trial in Australia (Acuna et al. 2018)

negative aspects of mechanical fuel load reduction is the associated costs that will increase the total costs in forest management. The survey participants also indicated that the mechanical fuel load reduction might cost more than control burning where both alternatives can be feasibly practiced. Half of the study participants believed that the recovered timber by this method could be commercially utilized to generate further income (Schirmer et al. 2018).

Often conventional harvesting plans in Australia contain a section for fuel load management planning such as post-harvest burning. Post-harvest burning helps with reducing fine fuel loads to protect thinned stands under prescribed conditions (Forests NSW, 2009). Acuna et al. (2018) tested mechanical fuel load reduction in New South Wales, Victoria and Western Australia. The sites were covered by various native forest species such as *Eucalyptus pilularis Sm.*, *E. microcorys F. Muell, E. resinifera Sm., E. punctate DC., Syncarpia glomulifera Sm., E. marginata, E. sieberii, E. obliqua* and *Corymbia calophylla.* Stocking was around 1500 stems/ha and tree diameter (DBH) was mostly less than 12 cm. The thinning operations aimed to remove trees with DBH under 15 cm to reduce the fuel load. Each study site applied a specific harvester (Valmet 450FXL, Komatsu XT430) and feller-buncher (CAT 511B) (Figure 7).

The harvester's productivity varied from 6.4 to 13.0 m^3/PMH_0 while the feller-buncher's productivity had a variation of 16.2 to 26.5 m^3/PMH_0 depending on DBH. Table 1 presents a summary of the methods and machine performance for mechanical fuel load reduction and salvage logging recovery. The most common method for mechanical fuel load reduction was cut-to-length using a harvester (to fell and process the trees to logs) and forwarder (to extract the logs to the landing). This method has been widely applied in Canada, the USA, Europe, and Oceania. In some countries (e.g., Australia and the USA) the whole tree method is also applied for fuel load reduction in natural forests and plantations. This method was often conducted using feller-bunchers (to fell and bunch the trees), grapple skidders (to extract the whole trees) and chippers/grinders (to process into wood chips). The majority of the mechanical fuel load reduction projects yielded the extra fibre which was used for bioenergy purposes. The number of published salvage recovery studies were limited compared with studies on mechanical fuel load reduction. A European case study on timber salvage recovery applied a cut-to-length harvesting method. Windthrown trees were firstly processed to logs by a harvester-processor, then the logs were extracted using medium and heavy size forwarders to the roadside.

Table 1. Summary of applied harvesting machines and methods for salvage recovery and mechanical fuel load reduction

Region/ Country	Method	Machine/model	Productivity (m^3/PMH)	Reference
North America Canada	Fuel reduction by Mechanized cut-to-length	Ecolog 550D harvester, Ponsse Buffalo King forwarder	16.6- 30.1 10.7-19.8	Dyson and Hvenegaard (2021)
USA	Fuel reduction by Manual cut-to-length Mechanized cut-to-length Whole tree	Chainsaw, Forwarder Harvester, Forwarder Tracked feller-buncher, Grapple skidder, Delimber, Loader	n/a n/a n/a n/a	Larson et al. (2000) Artosi et al. (2008) Rummer et al. (2003)
Europe Italy	Salvage recovery using cut-to-length harvest method Salvage recovery using whole tree method	Forwarder (John Deere 1210 E, Ecolog 574 B, Ponsse Buffalo) Chainsaw, Valentini V600/ M3/1000, Konrad Woody 61H	14.4-23.0 18.2-24.5	Cadei et al. (2022) Spinelli et al. (2023)
Oceania Australia	Fuel reduction by cut-to-length and whole tree	Harvester (Valmet 450FXL, Komatsu XT430) Feller-buncher (CAT 511B)	6.4 to 13.0 16.2 to 26.5	Acuna et al. 2018

Conclusions

To select a suitable harvesting method Ximenes et al. (2017) emphasized there is no one-size-fits-all solution to mechanical fuel load reduction operations. Forest companies will need to adequately assess the work conditions and identify the desired outcomes (such as retaining biomass or recovery for further use) to select the suitable harvesting machine and method. Larson et al. (2000) indicated that applying an old and slow skidding system (in manual and mechanised cut-to-length operations) in North Arizona led to an increased operating cost and thus to an unprofitable fuel reduction and forest restoration treatment. The application of well-suited and updated equipment could help in the reduction of operation costs. The harvesting contractor may require shifting toward methods and technologies which are effective in small tree harvesting to produce higher value products within mechanical fuel reduction programs (Rummer et al. 2003).

The Canadian experience indicated that when applying a harvester and forwarder in thinning operations, pilling residues in two sections, including large pieces and small branches, could help improve the harvester productivity for biomass harvesting. Forwarder productivity could be improved if the biomass materials were piled on the bunk and the biomass was loaded as much as practically possible in each turn, which is consistent with suggestions provided by Artosi et al. (2008) in Minnesota, USA. The stumpage cost was high in the fire risk mitigation trials therefore Canadian researchers suggested that future research could aim to eliminate stumpage, which can make fire risk mitigation projects more financially viable (Dyson and Hvenegaard, 2021).

From a marketing perspective, thinned materials from fuel load reduction trials may have the characteristics that could be used for biofuel; however, it was not available at the required fibre cost in North Arizona according to Larson et al. (2000). When the energy market is available (e.g. for transport distance from 60 to 100 km) the materials recovered from salvage harvesting in windthrown areas could be economically viable (Conrad IV, 2023).

Considering the environmental impacts associated with salvage harvesting, Lindenmayer et al. (2004) recommended to properly plan for a suitable timing and intensity of the salvage harvesting and to set the appropriate policies before forest fires occur. That could help in the reduction pf consequent ecological impacts. They suggested a policy for exempting large areas such as national parks, natural reserves, and watersheds to improve water quality. Nakamura (1996) emphasized that whole tree biomass harvesting presented a potential risk for wildlife and site productivity due to the removal of whole trees from the forests. Thus, mitigating such a risk could be the subject of future research.

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