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Harvesting Systems for Steep Terrain in the Italian Alps: State of the Art and Future Prospects

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Abstract

Steep slope forest operations in Central Europe and in particular in the Alps are strongly related to the adoption of the cable-based harvesting system, even if innovative ground-based harvesting systems have been proposed in the last years. In this context, the present work aims to acquire a thorough knowledge of yarding technologies used by the logging companies of the central Italian Alps, to evaluate their professionality in steep slope forest operations, and to predict the potential diffusion of innovative steep slope harvesting systems in the area. The results show a large number of logging companies (106) working with cable-based systems and in particular with four different standing skyline yarding technologies. The analysis of professionality in using cable cranes shows big differences between the companies. In particular, it identifies a consistent group of companies with a highly mechanized machinery fleet and high skills and experience in steep slope forest operations. These enterprises evidence a still limited potential diffusion of the innovative ground-based harvesting systems in the area, even if it is theoretically possible according to the GIS analysis of morphology and forest road network.

Keywords: logging companies, cable yarder, cable-assisted technology, tethered machine, steep terrain

1 Introduction

The expansion of forest mechanization on steep terrain is one of the main challenges of forest engineering. Forest operations on steep terrain are generally characterized by low productivity and high costs because of the complexity of the morphology and the lack as well as the inadequate standard of the forest road network [1]–[3]. Slope and terrain roughness negatively affect the application of the common ground-based harvesting systems that can normally safely operate on slopes below 30-40% [4]. In these conditions, the cable yarding system and, in limited situations, also the airship-based system are the only harvesting systems able to operate efficiently [5], [6].

Different configurations of cable yarding technologies are widespread in all mountainous regions of the world, such as in Central Europe, the Pacific North-west of the United States, and Japan [7]. In Central Europe, and in particular in the Alps, there is a long tradition of thinning and selective cutting operations. This type of silviculture regime requires a lateral movement of logs from the stump to the cable road and, for this reason, the predominant cable system is the standing skyline. In this configuration, the skyline is fixed to both ends and the load, hooked to a carriage, is moved on the skylines by the main line, which in some cases has to be combined with a haul-back line for valley mounted yarders and downhill wood extraction [8], [9].

Cable yarding is generally considered an environmentally friendly harvesting system because of its low impact on both soil and residual stand, but the excessive set-up time and high running costs determine generally low gross productivity [10], [11]. Moreover, cable yarding operations need appropriate planning and dimensioning to respect safe working conditions, and require high skills and effective teamwork [9], [10]. Even if cable-based harvesting systems have reached a high level of mechanization and automation [8], [12], [13], considering also the introduction of radio controlled chokers [14] or motorized carriages [15], their high levels of manual and motor-manual tasks such as tree felling or setting chokers lead to a corresponding difficulty in obtaining adequate insurance cover [16], [17].

Though cable yarders are common on steep terrain, including the Italian Alps [18] and partly also the Mediterranean areas of Italy [19], [20], their low production rate and high safety risks have oriented research to the identification of different steep slope harvesting systems. This led to the extension of the safety operation range of ground-based harvesting systems through the development of special traction devices and undercarriages [21]. Harvesters with independently suspended tracks or wheels mounted on hydraulically driven arms, and machines fitted with a winch synchronized with the wheels traction and self-levelled boom and cabin are the main developments introduced in ground-based harvesting system in the last years [22]. In particular, the introduction of synchronized winches, able to increase traction control and reduce slippage, should allow the tethered machines (cable-harvester and cable-forwarder) to operate up to a range of 75-85% slope, increasing the overlap area between the ground-based harvesting system and the cable-based harvesting system, where there is an adequate ground roughness [21].

According to the multi-criteria decision model developed by [23], the possibility of diffusion of the innovative ground-based systems instead of cable-based system might be attributed to higher system productivity and no set-up times, higher contribution margin because of lower harvesting costs, greater working safety as a result of fully mechanized harvesting system, fewer impacts on the remaining stand because of a more careful extraction process and lower greenhouse gas emissions. On the other hand, the use of ground-based harvesting systems on steep terrain could increase the impact on the soil due to the high bearing pressure of heavy cable-forwarders and it could reduce the number of employees needed for harvesting the same timber volume. However, there is insufficient knowledge to define the real positive or negative aspects of ground-based harvesting systems integrated with a synchronized winch.

In this context and in particular for the central Italian Alps, this paper aims to evaluate the diffusion and characteristics of the cable-based harvesting system and to analyse the logging companies working with this system on steep terrain. In particular, the goal is to acquire a thorough knowledge of yarding technologies used on steep terrain and classify the logging companies in terms of professional capability in the use of cable-based harvesting system. Again, by considering the characteristics of the logging companies and of the morphology and forest road network, the potential diffusion of the innovative ground-based harvesting system based on tethered machines will be assessed in the case study area.

2 Materials and methods

The study area is located in the central Italian Alps and more specifically in the Alpine provinces of the Regione Lombardia, where forests cover more than 560 000 hectares, 85% of which is in mountainous areas [24]. The logging companies operating in the study area and their contacts were identified through consultation of the regional register of logging companies, published periodically by the Regione Lombardia, and data provided by the regional forest offices (ERSAF-Ente Regionale per i Servizi all'Agricoltura e alle Foreste, and Direzione Generale Agricoltura). Each company was then contacted by telephone in order to identify those operating with cable-based harvesting system, their machinery and their availability for a face-to-face interview. A total of 258 logging companies were contacted (95.6% of the logging companies in the regional register at July 2014).

In order to understand not only the technical features of the machines but also the rate of intensity and use conditions of cable-based harvesting system, the management system of the landing site, and the experience in planning and installing methods of cable crane lines, a sample of 55 logging companies (52% of the companies working with cable-based harvesting systems) was selected. Data collection from these 55 companies was conducted through face-to-face interviews and a semi-structured questionnaire submitted during spring and summer 2014. The parameters acquired during these interviews are reported in Tab 1.

Tab. 1. Parameters acquired during the face-to-face interviews

Section	Parameters
Rate of intensity and use conditions of cable-based harvesting systems	Harvesting systems adopted
	Rate of intensity in the use of cable-based harvesting systems
	Use conditions of different harvesting systems
Management of the landing site	Working system adopted
	Organization of the yarding crew
	Communication system adopted
	Organization of the landing site
	Residues processing
Experience and procedures in planning and installing cable crane lines	Survey of skyline corridor profile
	Marking of the skyline corridor
	Identification, choice, and installation of anchors and supports

The collected data were then summarized in four sections with the aim of defining the professional capability in using the cable-based harvesting system by the logging companies. Each section was evaluated according to four different levels so logging companies reach, for each section, a partial score ranging from one to four. The total score, derived from the sum of the partial ones, defines a graded list used to identify three different groups of logging companies according to their professional capability in using cable cranes. Tab. 2 shows the evaluation scheme adopted and the partial score of each section.

The sorting of the logging companies in terms of their professional capabilities in the use of cable yarding system, and consequently in operating on steep slope terrain, was used to separate the group of companies with the highest performance. This group was considered as the group of companies potentially interested in the introduction of innovative steep slope harvesting systems, such as the tethered vehicles recently promoted by a lot of machinery producers. For this reason, 40% of these companies were interviewed in order to understand their knowledge of the innovative ground system based on tethered machines, and their opinion about the applicability of this system in the study area. These declarations were compared with the theoretical potential diffusion of innovative ground-based harvesting systems evaluated through a GIS analysis.

Tab. 2. Scheme used for professional capability evaluation

Cable yarding technologies supply	**Score**
Logging company has more than one cable yarding technology and all its machines comply with the Directive 2006/42/EC [25]	4
Logging company has more than one cable yarding technology but not all its machines comply with the Directive 2006/42/EC [25]	3
Logging company has just one cable yarding technology and all its machines comply with the Directive 2006/42/EC [25]	2
Logging company has just one cable yarding technology but not all its machines comply with the Directive 2006/42/EC [25]	1

Tab. 2. (Continued): Scheme used for professional capability evaluation

Rate of intensity in the use of cable cranes(1)	**Score**
Forest operations are the main activity of the company and the rate of intensity in using cable-based systems is very high	4
Forest operations are the main activity of the company and the rate of intensity in using cable-based systems is high	3
Forest operations are the main activity of the company and the rate of intensity in using cable-based systems is medium	2
Forest operations are the main activity of the company and the rate of intensity in using cable-based systems is null or low, or forest operations represent just a secondary activity	1
Management of the landing site	**Score**
Very high mechanization of the harvesting system. Timber managed through specific machines set-up with processor and use of innovative working systems(2)	4
High mechanization of the harvesting system. Timber managed through specific machines and use of innovative working systems	3
Medium mechanization of the harvesting system. Timber managed through specific machines or with versatile machinery used in other work phases (cranes of forestry trailers) and use of traditional working systems	2
Low mechanization of the harvesting system. Timber managed through versatile machinery used in other work phases (cranes of forestry trailers) or manually, and use of traditional working systems	1
Experience and technical knowledge	**Score**
Very high experience in setting up different cable yarding systems or difficult profiles lines, and very high skills and technical knowledge in planning and installing the lines(3)	4
High experience in setting up one cable yarding system or simple profile lines, and low skills and technical knowledge in planning and installing the lines	3
Low experience in setting up cable yarding systems, and good skills and technical knowledge in planning and installing the lines	2
Low experience in setting up cable yarding systems, and low skills and technical knowledge in planning and installing the lines	1

(1) The rate of intensity in the use is expressed in terms of percentage of the total volume of timber processed annually. Very high >91%; high 61-90%; medium 41-60%; low 11-40%; null <11%.
(2) Innovative working systems mean harvesting systems based on whole tree work, with wood processing at the landing site and residues utilization for chip production.
(3) Skills and technical knowledge in planning and installing the lines were evaluated considering the good practices defined by the technical manuals available in the literature [26]–[29].

3 Results and discussions

From the analysis of the data collected, the cable-based system results as the most common steep slope harvesting method used by the logging companies in the study area. The current diffusion of conventional ground-based harvesting systems based on harvesters, skidders, and forwarders is still limited to a few logging companies, as also individuated in [18]. Just three forwarders and one skidder have been found in the study area. Also, the use of airship-based harvesting system, even if higher than other areas [30], is still limited to special conditions and few cases.

The use of a helicopter in forest operations is usually confined to the transport of sled yarders in the forest.

3.1 Cable-based harvesting system

The cable-based harvesting system is the most common harvesting system used by logging companies in the study area for steep slope forest operations. The number of logging companies working with this system (Fig. 1) is 106 (41% of the 258 analysed), while the total number of cable yarders is 168.

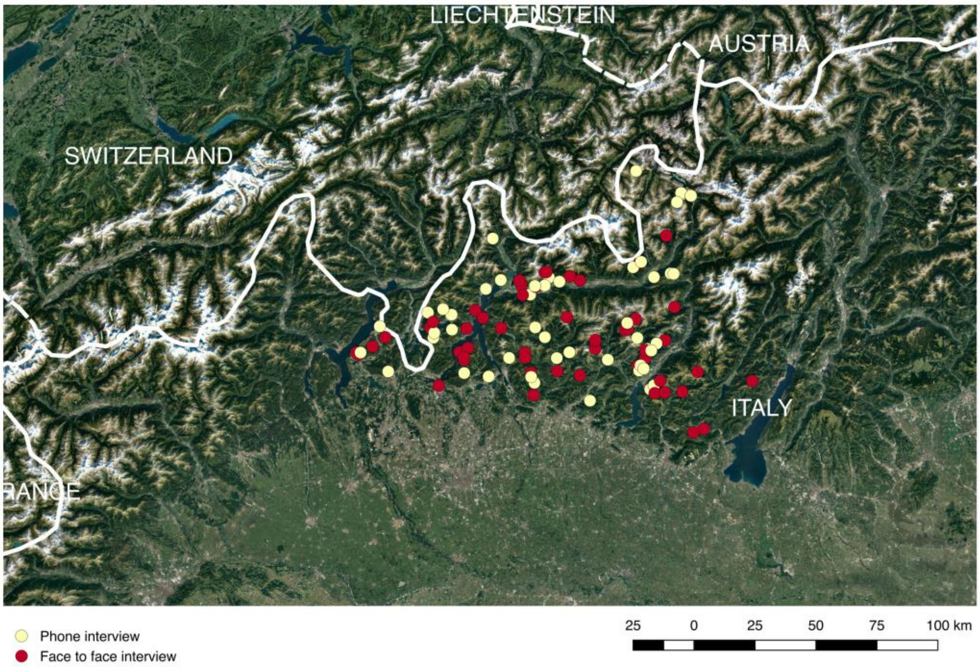

Fig. 1: Distribution of logging companies equipped with cable yarders and evidence from those interviewed face-to-face and by phone

The cable systems used in the study area are based on the standing skyline configuration, as is common in Central Europe. Four different cable yarding technologies (Fig. 2) have been identified: sled yarders, mobile tower yarders, self-propelled carriage-based yarders, and mobile yarders without a tower. The frequency distribution of the different technologies is reported in Tab. 3.

Fig. 2: a) Sled yarder; b) Mobile tower yarder; c) Self-propelled carriage-based yarder; d) Mobile yarder without a tower

Table 3. Frequency distribution of the cable yarding technologies

Cable Yarding technology	**Logging companies (n)**	**Cable cranes (n)**
Sled yarders	85	109
Mobile tower yarders	19	25
Self-propelled carriage based yarders	26	26
Mobile yarders without a tower	8	8

Sled yarders are the most common yarding technology used by logging companies in the study area. This system covers almost 65% of the total number of cable cranes and is used by 80% of logging companies working with cable-based systems. The average age of these machines is 21.8 years (σ = 11.45 years) while the average power is 51.6 kW (σ = 21.34 kW). According to the declarations of the logging companies, this technology is widespread especially for downhill wood extraction and long distance cable yarding (optimal distance declared 800-850 m). The logging companies appreciate the versatility of this system and the possibility of using it in inaccessible areas, even if they recognize the too high set-up time and difficulty in installation.

Mobile tower yarders represent almost 15% of the total number of cable cranes used by logging companies in the study area. The two-line system, based on a skyline and a mainline and usable just in gravity systems, is the most frequent (76%), while the three-line system is limited to six machines. Tractor mounted yarders are the most common vehicle equipment (44%), followed by cable cranes installed on towed wheel trailers (40%) and on self-propelled track undercarriages (16%). The machinery fleet of the logging companies in the study area do not include any truck mounted yarders or processor tower yarders. The average age of the mobile tower yarders is 6.8 years (σ = 8.51 years), while the average engine power or, in the case of tractor mounted yarders, the average power delivered by the tractor at the power-take-off (PTO), is 104.7 kW (σ = 41.09 kW). The mobile tower yarders are mainly used for short distance cable yarding (optimal declared distance 400-450 m) and for uphill wood extraction. This type of cable technology is not so common in the study area because logging companies evaluate the forest road network as not adequate. In particular, the low rate of forest roads for uphill wood extraction and the limited width of the pitches for positioning the cable yarders are considered the main limiting factors. However, the logging companies who are currently working with this type of technology are completely satisfied and they use it primarily or exclusively, even if they also have different yarding technologies.

Self-propelled carriage-based yarders are more than 15% of the cable cranes and are used by one logging company in four working with cable systems. The introduction of this technology in the study area is recent (average age 3.5 years, σ = 3.73 years) given that more than 42% of the machines have been bought between 2013 and 2014. The average engine power is 71.6 kW (σ = 8.16 kW). Some of the main advantages of this system, stressed by the companies, are the relatively low price compared with other technologies with the same operative capacity, and the ease in installing and conducting the system. On the other hand, a lot of logging companies show great uncertainty about this system mainly because of the high economic damage in the case of derailment and subsequent fall from the skyline, the high load on the intermediate support due to the heavy weight of the carriage itself, and the high skyline deterioration. The optimal yarding distance declared by the logging companies for this system is 500-550 m. More than a quarter of logging companies (27%) use this system in association with a mobile tower yarder or a skyline-winch with a tower in order to obtain the advantages of both systems.

Mobile yarders without a tower are the least common cable yarding technology in the logging companies of the study area. They represent less than 5% of the total number of cable cranes and they are present in less than 8% of companies. The average age of this technology is 4.1 years (σ = 3.72 years) while the minimum power required by the tractor at the PTO is 49.5 kW (σ = 6.02 kW).

The main reasons for the low diffusion of this system are its low productivity rate and the limited maximum yarding distance (optimal yarding distance declared by the logging company is 200-300 m). The main advantages of this yarding technology are its very low price and short set-up time. It is used primarily for firewood extraction in private coppice.

The age and power data of the machines are not normally distributed. For this reason, the analysis of the differences between the four technologies requires a non-parametric test comparing the median instead of the average. In terms of age, the application of the Kruskal-Wallis test and the Bonferroni correction show that the median age of sled yarders is statistically higher ($p<0.05$) than all the other technologies. The ages of the mobile tower yarders, self-propelled carriage-based yarders and mobile yarders without a tower are statistically equal to each other.

Regarding the power of the machines, the Kruskal-Wallis test shows a statistical difference between the groups ($p<0.05$) and in particular between the high power of the mobile tower yarders versus the power of sled yarders and mobile yarders without a tower.

3.2 Professional capabilities of logging companies in the use of cable yarding

The technical features of the cable machinery fleet and the other parameters required during the face-to-face interviews have been used to sort and classify the logging companies in terms of their professional capabilities in using cable-based harvesting systems, according to the multi-criteria scheme proposed in Tab. 2.

The results show the presence of a consistent group of logging companies (27%) with a **high level of professional capabilities**. These companies have a machinery fleet of 35 cable cranes. Sled yarders, track-mounted tower yarders, trailer-mounted tower yarders, and self-propelled carriage-based yarders are the most common technologies in this group. One logging company in this class out of three has a processor for mechanized wood processing at the landing site. The intensity of use of cable-based harvesting systems is extremely high (95% of the total volume of timber processed annually) as well as the technical knowledge and experience in the use of the cable systems. 60% of the logging companies evaluated shows a **medium level of professionalism** in the use of cable systems mainly because of some deficit in machinery inventories or in the knowledge of the proper installation methods. The yarding technologies in this group are represented mainly by sled yarders, tractor mounted tower yarders, self-propelled carriage-based yarders and mobile yarders without a tower. These companies have to overcome some problems but have ample room for improvements. A small group of logging companies (13%) is characterized by a **low level of professional capabilities** in using cable systems mainly because of outdated machines associated with limited technical knowledge. The rate of intensity in the use of cable based-harvesting systems is also limited (46% of the total volume of timber processed annually).

3.3 Future prospects in steep slope harvesting systems

The recent introduction of cable-assisted machines on steep terrain also in the Alps could be an alternative for harvesting and extraction operations in the central Italian Alps. According to [22], [23], cable-assisted machines can operate on slopes of up to 60% when safety conditions are observed. This is an average limit variable depending on relief and soil bearing capacity. However, slopes up to 30% are generally recognized as feasible for wheeled machines without a synchronized winch, while cable cranes are supposed to be able to work up on very steep terrain. As a consequence, by considering conifer stand area in the central part of the Italian Alps within a distance of 350 m from the nearest forest road practicable for trucks and forwarders, and by considering a terrain slope ranging from 30% to 60%, a total of 19 643 ha could be suitable for tethered machines. Again, by analysing the cable line installations (years 2011-2015) that were completely inside or partially crossing the potential area where cable-assisted machines can operate, the average length of the cable installation, as declared by the forest technicians to the regional forest offices is 438.85 m (σ = 224.571 m). From the same analysis about 41% of the installations report an installation length within 350 m, potentially achievable also by the innovative ground system based on cable-assisted machines. However, the current opinion of the highly professional cable-based logging companies about the introduction of innovative ground-based systems is still not very encouraging. In their opinion, morphological conditions of the harvesting sites are a real constraint to the applicability of ground machines, even if equipped with a synchronized winch. In particular, the main limiting factor is terrain roughness. Another constraint could be the potentially high environmental impact of the ground vehicles moving on steep terrain. Logging companies highlight that the forest legislation in force would not allow the use of heavy machines because of too high soil damage (compaction and rutting).

4 Conclusions

Steep slope forest operations in the central Italian Alps are strongly associated with the application of the cable-based harvesting system. This is demonstrated by a large number of logging companies operating with these systems and by the high number of cable cranes. Even if in the international context the cable-based harvesting systems are currently mainly represented by mobile tower yarders, in the study area the predominant technology is based on sled yarders. Analysing the logging companies in detail, it emerges that there are big differences between them, mainly in terms of technological availability and professional capabilities in using cable-based systems. These differences allow to separate a group of logging companies (27%) with a consistent machinery fleet, high production capacity, efficient management of the yarding crew and harvesting site, and high skill and technical knowledge of the planning and installation methods of cable crane lines. This group of logging companies with high professional capabilities in steep slope forest operations is considered as the group of companies potentially interested in the introduction of innovative steep slope harvesting systems, such as the tethered vehicles. The diffusion of this innovative system, even if theoretically possible as defined by the GIS analysis, is still not taken into account by these logging companies. In their opinion, the maximum level of mechanization in forest operations in the study area is based on cable cranes and processors. The tethered machines are considered inapplicable due to the morphology and the high environmental impact not permitted by the forestry legislation. Future prospects for innovative ground-based harvesting systems for steep terrain have to be carefully evaluated as was done for cable logging in [12]. In particular, the declarations of the logging companies suggest the need for a clear evaluation of the safe operating limits of this system, as anticipated in [22], and of its environmental impacts. In these terms, besides soil and stand damages, in order to clearly define the total environmental impact of the innovative ground-based system compared with the cable-based system, an extensive Life Cycle Assessment (LCA) analysis should be applied [31], [32].

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