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ANALYSIS OF SMALL DIAMETER ENERGY-WOOD HARVESTING MACHINERY, EQUIPMENT AND SYSTEMS

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Contents

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Abstract

Small tree harvesting for energy wood could offer an income in thinning of young stands, hardwood coppices, and cutting of dedicated coppice plantations (SRC). The introduction of low cost harvesting solutions, with high productivities, low stand impacts and higher mass removal are considered the main innovation objectives in forest biomass harvesting. The aim of the study was to evaluate improvements and limits of the *Whole Tree System* technologies in "small" and "large scale" harvesting conditions. The analysis of small scale harvesting was carried out trough experimental field comparisons of full tree technologies based on traditional machines and methods, analyzing biomass removal, achievable productivities and silvicultural results. These studies were performed in different young stand conditions in Italy, in order to identify the best machines, equipment and systems for full tree harvesting, in each condition. Full tree harvesting showed to increase the mass removal up to 30%, when compared to traditional firewood harvesting in coppices and stem harvesting in thinning of pine stands. From the work times analysis resulted a possible significant increase of operator productivity and improved work ergonomics applying a modified frame to a traditional chainsaw in the lift felling-bunching technique. In all cases was noticed a possible biomass cost reduction, if acting on tree bunching and machine payloads, using the right extraction equipment. A field study and theoretical simulation of young stands thinning in Sweden allowed to compare energy wood and pulpwood system in large scale. The results showed the possibility to double the removal and to reach the economical profitability of full tree harvesting in stands where pulpwood removal is actually a cost. The study of SRC plantations showed the possible yields in different land fertility conditions and the needing of improvements in actual harvesting systems to reach economic and environmental sustainability. The study results allowed to model productivities in biomass cutting and haulage in small scale and large scale conditions, these results integrated with existing literature information allowed to give an economical evaluation of full tree harvesting at different scale. Finally the thesis underlined the needing of new harvesting solutions to reduce the biomass cost and to find a compromise between biomass, site nutrients removal, and environmental impact.

Keywords: bioenergy, small diameter trees, energy wood, forest harvesting, small scale forestry

INTRODUCTION

Since the '70s with the first world energy crisis, many developed countries started to promote bioenergy and to use biomass as energy alternative to fossil fuels, so launching promotional activities and financing research and development of suitable technologies.

In this context, forest biomass certainly represents an interesting solution (Schlamadinger et al. 2004). Since the source of energy is locally available it could promote socio-economic development of rural communities, holding the exodus from remote farm areas and contributing to the sustainable management of forest resources (Ciccarese et al 2006).

Forest biomass offer a sustainable alternative to current energy sources, since the release of 25-50 energy units for every unit spent in biomass production, coupled with CO_2 emissions 10-20 times inferior to fossil fuels in electricity conversion (Schlamandinger & Marland 2001). It is well known that CO_2 emissions in biomass combustion are the same fixed by the biomass growth, in addition emissions in biomass harvesting and conversions are limited to 4-7 kg CO2eq./MWh (Wihersaari 2005).

According to the International Energy Agency in 2005 the biomass use in industrialized countries rapidly increased, reaching in 2003 an amount corresponding to 1 Gtoe, so representing 14.3% of total energy balance. Biomass account 35% of energy consumption in developing countries, while in industrialized countries representing only 3.2% of total energy consumption. According to the same Agency in 2020 biomass could reach 2.2 Gtoe and 3.8 Gtoe in 2050 (IEA 2005).

Several EU Directives promoted growth of sustainable energy resources in different sectors. The objectives of EU policies are so ambitious that the availability and prices of biomasses could be limiting factors for future development, so it will be needed an integration of different biomass sources: forestry, agricultural residues and biodegradable component of solid municipality waste. These ambitious goals can have a strong impact on forest products market, as the bio-energy sector is becoming an actor with increasing market power.

It is difficult to predict an increase in percentage of harvested forest increment, used as bio-energy, although the percentage directed to energy conversion it's expected to grow in coming years.

The use of small wood for energy production will depend on prices of wood and especially the price of pulpwood, paper and energy production (Karjalainen et al. 2004).

The energy consumption increased further than 20% from 1985 to 2003. Oil, coal and natural gas nowadays represent 80% of energy consumption in Europe. Two thirds of these energy resources are supplied from external EU countries, meaning high risks connected to external countries policies. In addition the emissions from fossil fuels are the major source of greenhouse gases, contributing to global warming. The approach to overcome these issues includes energy saving, development of alternative resources and international cooperation. So the efficient use of renewable wood biomass can balance the use of fossil resources and energy imports (Karjalainen et al. 2004).

Forest residues, residual wood from industries and short rotation forestry crops are the main sources of biomass supply. The annual availability of forest fuel in Europe was estimated in 56 million o.d. tonnes, corresponding to approximately 280 TWh of energy or 24 Mtoe. This amount corresponds to 24% of present renewable energy use in the EU. The largest volumes of forest residues are available in Sweden (15 Mm^3) Finland (11.4 Mm^3), France (8.6 Mm^3) and Germany (6 Mm^3). Consequently, the largest reserves of forest biomass in Europe are mainly in Finland, Sweden, Germany and France but also Spain and Poland showed considerable forest biomasses for energy production (Karjalainen et al. 2004).

In the standpoint of the White Paper, EU 1997, renewables should reach 12% of EU energy consumption in 2010. So in Italy, the Ministry of Agriculture and Forestry in 1999 adopted a national program to enhance the agricultural and forestry biomasses (PNERB), with the objective to achieve 10Mtoe from biomass in 2010-12. While the European Commission with the Biomass Action Plan in 2005 set the goal to reach 43 Mtoe by forest biomass and energy dedicated agricultural crops.

The objectives of national and international policies depend from a large number of factors, but principally related to: growth of efficiency in bio-energy systems (logistics, marketing and technology), increase of renewable biomass harvesting from forests and from energy dedicated crops. Therefore Italy is searching for sources of "clean" energy with enormous attention to forest biomass, but without effective planning schemes (Spinelli et. al. 2008). In practice, only the increase of fossil fuels and carbon credits prices may possibly boost the price that costumers would pay for energy wood, generating an additional quantity of harvested wood resources (Ciccarese et al. 2006).

In the Nordic Countries forest biomass is already a renewable resource widely used in energy production, particularly in Sweden. The annual production of energy in Sweden is approximately 625 TWh (Swedish Forest Agency 2008) of which about 19.5% comes from bio-energy. Forest fuels represent approximately 7.5 TWh (1% of total) (Athanassiadis et al. unpub.). Currently there is a growing demand for energy wood, since Sweden supposed to completely replace fossil fuels by 2050. The potential of forest fuels (considering the economic and ecological restrictions) is about 53 TWh (8.5% of total energy) (Athanassiadis et al. unpub.).

It is supposed that a substantial proportion of the forest biomass potential will come from young stands, which in Sweden represent 21.4% (4.9 million hectares) of national forest area (Swedish Forest Agency 2008). From these stands can be extracted about 5 million tons of dry material per year, corresponding to approximately 23 TWh of energy (Nordfjell et al. 2008). Unfortunately, these stands do not receive necessary thinning, due to the low demand for small wood as raw material and too high costs of pre-commercial thinning (PCT).

Usually in the first commercial thinning (FT) mainly pulpwood is produced, then 20-30% of the stem is left as residue (Hakkila 2005) and consequently only a small portion of biomass potential is used.

When the obtainable pulpwood exceeds 20 m^3 ha^{-1} integrated harvesting of wood for industrial use and for energy seems to be more convenient or in alternative a delayed thinning practice (Heikkila et al. 2007), compared to pulpwood harvesting. The integrated harvesting of energy wood and pulpwood demonstrated the possibility to increase the harvested biomass up to 50% (Jylhä & Laitila 2007). In this practice the smallest diameter of pulpwood plays an essential role on the distribution of harvested biomass between industrial or energy use (Sirén et al. 2006), especially when the basal stem can find a noble destination (saw logs) while a large percentage of the wood is not suitable for industry (Suadicani 2003). The integrated harvesting of pulpwood and energy wood (chips) is often more expensive than harvesting only pulpwood, since more machines are working in the same area. In order to reduce machines and costs were introduced bundle harvesters (Jylhä 2004), but these machines are still characterized by low productivities. Recent studies showed that harvesting the whole tree in the first thinning (FT) and addressing whole biomass to energy can be a cost-effective alternative compared to pulpwood harvesting in young stands. (Sirén et al. 2006). In whole tree harvesting delimbing is avoided and removed biomass increased by 15-50%, so the harvesting productivity can increase 15-30%, therefore the cost of the tree hauled to roadside can be reduced from 20 to 40 % (Hakkila 2003).

Energy wood potential in Italy

Since the ‘90s, according to ISTAT surveys, wood harvesting in Italy substantially increased and particularly energy wood, representing 2/3 of the yearly total amount (ISTAT 2008). These quantities, using the conversion criteria of Eurobserver (2005) were translated to 1.09 Mtoe, but official statistics do not included information about informal firewood harvesting, widely spread in Italy. Moreover, these calculations should include biomass obtained from trees grown outside forest areas (approximate in 0.14 Mtoe).

Coppice stands represent 42% of Italian forest surface, therefore playing an important role in country management and economy, these stands were usually harvested for firewood, but may offer also other products, like fence poles or pulpwood. Biomass market offer a substantial opportunity to increase removals, in order to reach economic sustainability of current practices in difficult terrain conditions, but current harvesting costs must decrease, particularly in degraded or steep terrain coppices, where nowadays biomass harvesting is not economically feasible (Verani et al. 2008). In the Italian coppice reality firewood doubles energy wood (chips) price, so whole tree chipping it is not considered profitable. In traditional firewood harvesting crown residues, undersized for firewood production (with diameter lower than 3-4 cm), are abandoned in the stand, in future it will be possible to recover this material as energy wood chips.

In Italy from the beginning of XXth Century were realized widespread reforestations, these activities continued up to the Second World War. Most of the barren areas were planted with conifers, considered more appropriate in poor soil conditions. So in unfavourable soil conditions the tree selection was addressed to the pines species, which are particularly tolerant, in particular *Pinus nigra* was the most omnipresent species. In warmer climate conditions were planted Mediterranean pines, particularly *Pinus halepensis* and *Pinus pinaster*. Nowadays most of the pine reforestations are in difficult stand situations, with excessive density, so starting intra-specific competition, producing trees particularly vulnerable to various stress factors and especially to aridity. Therefore it is essential to carry out thinning, with different features, appropriate to stands conditions and management strategies. Ideally thinning should be of moderate intensity, so that residual trees will not be stressed and frequent in short time intervals to stimulate tree growth (Ciancio 1986). Unfortunately selective thinning with a low removal intensity involves high costs, so often these treatments must be intensified to obtain a net income. Accordingly in low quality stands it is more advisable a geometric thinning, opening corridors and allowing machines passages, but also this solution rarely allows complete economic sustainability in energy wood harvesting (Magagnotti et al. 2009).

For the calculation of energy wood potential in Italian forests were adopted criteria of APAT (2003). A first evaluation can be obtained from clear cut residues in high forest stands (branches, tops, bark). This quantity is usually expressed as percentage of timber assortments (15 to 35%), this figure ranges with wood species, geographical conditions and stand age. Considering the best hypothesis of collection in all available high forests, therefore, it is possible to reach 1.27 Mtoe of energy.

The residues of silvicultural practices (cleaning and thinning), carried out in high forest before the turn conclusion and in shelterwood forests with selective cuttings, are difficult to be assessed, since wood produced in these practices remains out of wood market, due to high harvesting costs. Furthermore biomass harvested in these silvicultural treatments could widely vary: practices are determined case by case, based on stands characteristics and management objectives.

Literature calculations were made only in optimal stand conditions with treatments regularly performed.

So the biomass achievable from thinning could be roughly estimated in 1-2 million m^3, corresponding to 0.23 to 0.46 Mtoe.

Coppice harvesting is mostly addressed to firewood production, so if we consider all stands productions as energy wood a maximum of 3.72 Mtoe could be achieved.

In Italy occurred a reduction of agricultural areas in last ten years, particularly affecting lands cultivated with traditional crops (-12.2% compared to 1990), these areas could provide marginal fields suitable for fast-growing plantations dedicated to energy wood production. These crops include SRC (Short Rotation Coppice) realized with *Populus spp., Robinia spp., Eucaliptus spp.,* cultivated in agriculture marginal lands. Assuming a careful production of 8 t dm/ha/year and assuming an SRC area of 100.000 ha in 2010, these forest crops may possibly produce 0.36 Mtoe.

Table 1: Energy wood potential in Italy (APAT 2003).

	Mtoe
High forest	1.27
Silvicultural practices (cleaning, thinning)	0.46
Coppice	3.72
SRC (Short Rotation Coppice)	0.36
Total	**5.81**

These calculations showed the relevance in Italy of small tree harvesting for energy wood. Accordingly the possibility to increase energy wood quantities can be identified in thinning practices, coppice harvesting, restoration of degraded forests (eg. fire damages restoration) and in energy dedicated plantations (SRF-SRC).

Harvesting systems in Italy

In recent years the minimum diameter of commercial logs assortments increased from 8-10 cm to 14 cm, meanwhile wood price dropped on the international market. In Italy price decrease was not balanced by increased harvesting productivity (Baldini et al. 2009, Ciotti & Pettenella 2007), thus reducing profit of silvicultural treatments, particularly in case of small tree harvesting.

Nowadays in Italy tree felling is mainly performed motor-manually with chainsaw, this machine does not reach the harvester productivity, however the latter is common only in Alpine Region, especially in spruce high forests. Harvesters are characterized by productivity of 12-18 m^3/h, but these machines require an high level of operator training and wood volumes larger than 8000 m 3/year in order to be economically sustainable. Alternatively harvester heads can be attached to standard excavators or to wheeled tractors with a minimum power output of 80 kW, provided of hydraulic cranes and with specific structural changes and adequate hydraulic pumps (Cavalli, 2004).

In most of Italian forest yards skidding and haulage are carried out by farm tractors, wheeled or tracked vehicles, equipped with winches, trailers or cages. The average power output of these machines is between 60 and 80 kW, with over 10 years of work life, so near the limit for technical obsolescence (Verani & Sperandio, 2005). In some Italian stands started the diffusion of forwarders, particularly in the Alpine Regions, these vehicles are equipped with steering frame and an hydraulic crane for loading and unloading the integrated trailer. The high forwarder mobility allows timber haulage from forest strip roads to roadside and possible transportation on forest road for longer distances (1500-2000 m) up to main landing areas, close to the ordinary traffic roads, so accessible by trucks.

Cable yarders are especially used in Alpine high forests, where it is possible to find complicated models, like three cables. Nowadays different cable yarder technologies are available also in small scale harvesting, usually based on two cables, easy to assemble, reliable, and particularly economic (Baldini at al. 2009).

The use of forest residues through chipping operations in the stand or at the landing is a common practice only in few Italian Regions (Neri & Piegai 2007). As the collection of residual forest biomass is often limited by slope terrain conditions, shortage of forest roads and by small landing spaces, which can affect the storage possibilities (Baldini et al. 2009).

The introduction of innovative low-cost work methodologies, with higher productivity, low stand damages, improved ergonomic conditions, and greater biomass harvesting are considered the main innovative objectives in forest harvesting in Italy, especially if addressed to energy wood (Spinelli and Verani 2000, Cavalli 2002, Marchi 2002). In innovative methods it is essential to account, in addition to technical, technological or organizational aspects, also items related to communication and diffusion of new machines and working systems. So only if technologies and working systems will be successfully tested and subsequently currently used, the innovations could guarantee a future technological development in the forestry (Marchi 2002). However, the use of updated machines and equipment represents an indispensable condition to achieve high working productivity, needed to reduce wood biomass harvesting costs (Spinelli & Verani 2000).

According to Hippoliti & Piegai (2000) in forest harvesting it is important to know and apply the best work system, in order to avoid trees and soil damage, to reduce work costs and enable useful forest practices, often considered too expensive.

In Italy it is possible to identify three main harvesting systems:

SWS Short Wood System: trees are processed at the felling site, bucking stems to final length for short wood haulage to the landing. This is the traditional system, commonly applied in firewood logging, particularly in the Italian coppice stands.

TLS Tree Length System: trees are delimbed at felling site and subsequently stems are hauled to the landing. The system allow to completely employ the payload of powerful tractors, especially when skidding small trees, the system is particularly suited for clear cuttings and stands without significant skidding obstacles. Frequently a subsystem, between the two previously described, is applied, skidding bucked stems with logs multiple of final assortment lengths (Cut to Length System). This compromise system allows to fully employ the capacity of cable yarder and tractors, avoiding excessive drawbacks in extraction of stems with lengths up to 20 m.

FTS Full Tree System (whole tree system): whole trees are hauled to the landing, without delimbing or bucking. This system is applied when tree branches could find a market (eg. poplar plantations), where the stand must be cleared from residues, or if it is possible to use processors at the landing (delimbing and crosscutting) and chippers. This system can be suggested for clear cutting, tractors skidding or cable yarders. The system must be avoided in poor soils conditions, cause the organic component losses, especially if branches could not find a market.

The work system selection, productivities, and therefore logging costs are determined by ground, stand and cutting features, and finally by forest accessibility, so by distances, layouts and characteristics of forest roads and skidding trails.

The main stand and cutting features to be considered in working system selection include:

- Slope (4 classes: 0-20%; 20-40%; 40-60%; 60-80%; >80%) 20% represents the superior limit for uphill skidding with tractors, while 30% the maximum slope for harvesters and forwarders and the minimum slope for gravity cable yarders and polyethylene chutes.

- Roughness (3 classes: low, average, uneven). The roughness describes the presence of obstacles hindering the passage of people and machine on flat terrain and the winching operations on slopes. The obstacles are created by rocks, holes or valleys carved by rain water. These obstacles could compromise winching operations. If the obstacles presence remains under 1/3 of the stand surface the winching operation find small difficulties and trails construction will be simple. When obstacles cover 1/3-2/3 of the stand surface winching is difficult and the construction of temporary trails is too expensive. In uneven terrain conditions obstacles are present in over 2/3 of the ground surface, so winching is too difficult and the use of a cable yarder will be desirable.

- Removal Intensity.

Low intensity, removals result under 30 m^3/ha, usually it includes cleaning, thinning, post fire restoration and accidental cuttings. These operations do not allow the economic sustainability of new temporary skidding trails, as cable yarder lines. So skidding is carried out by tractors, if the network of trails is sufficient, or the wood could be hauled by animals.

Medium removal of quantities from 30 to 80 m^3/ha, so it includes thinning or shelter wood cutting in selection forests. The most convenient practice will be skidding by tractors, but it requires an adequate network of forest trails. For small wood downhill haulage could result convenient to use chutes, otherwise in uphill direction it will be possible to use small cable yarders, particularly with mobile towers.

High Removal results over 80m^3/ha, so usually it includes clear cuttings in high forests. Every possible haulage systems can be used, however the cheapest are the tractors on lower slope and the cable yarder in steep terrain conditions. In coppice stands or when harvesting small wood on steep terrain it is convenient to use chutes, instead on slight slope the use of tractors with cages or trailers will be advisable.

- Stem dimensions: the average stem volume is the factor with the greatest influence on the work productivity and therefore on harvesting costs (Silverides & Sundberg 1989). If the stem volume remains under 0.2 m^3 (trees dbh under 25 cm) the increase of working time and subsequent costs is particularly high, this conditions are common when harvesting in thinning, young forests and coppices. In this case small tree haulage is addressed to pulpwood or energy wood, the chipping operation can be performed at the landing, without tree bucking or delimbing (Hippoliti & Piegai 2000). In thinning practices number and size of trees are low and the residual stand will present high density, since removal will be 20-40% in stems and 10-25% in total mass. So tree felling shows practical difficulties, resulting in high harvesting costs and a risks of excessive damages to residual stand. These troubles are particularly evident in pre commercial thinning and first thinning in dense stands, when there are no permanent skidding trails and it is difficult or too expensive to open temporary trails. Small wood is harvested also in coppices, when working conditions are particularly difficult and the operations reach low economic profitability, especially in coppice conversion or stumps thinning.

In addition to these specific stand factors, the harvesting productivity is particularly affected by operators technical skills, appropriate equipment and crew organization and efficiency (Hippoliti & Piegai 2000).

Energy wood harvesting

A large number of machines and harvesting system for forest biomass collection were developed at industrial scale (large-scale), following the energy crisis of 1973. These machines require high capital venture, so net incomes are possible through the complete annual utilization and reaching high productivity. At the same time were developed machines and equipment for temporary needs of small forest owners (small-scale) (Hakkila 1989). The preference between light, small sized and low technology machines or heavy, large sized and high technology machines is determined by local work conditions (Brenøe & Kofman 1990).

"Small scale" Harvesting the case of Italy

In Italy small scale machines are prevailing, due to the restrictive operational conditions, low investment capacity of forest enterprises (family or individual), small cutting surfaces (in average 1.03 ha) and especially the shortage of adequate forest infrastructure (Baldini et al. 2009).

To ensure an efficient collection of forest biomass it is essential to reorganize the supply chain. In silvicultural practices if it is achievable only energy wood it could be suggested a whole tree chipping, skidding and then chipping whole trees, or in suitable ground conditions, chipping trees in the stand and carrying chips to the landing. Instead to obtain traditional products and chips there are two main options: harvesting with the traditional short wood system and then coming back to collect the residual biomass, or skidding whole trees to the landing in order to recover in a single passage traditional assortments and residues. In this case whole trees skidding is convenient, especially when the amount of residual biomass is low, so the double passage is not justified.

Moreover if ground conditions do not allow machine ingress into the forest are required cable systems, so the whole tree system remain the only efficient solution for biomass recuperation (Spinelli et al. 2006).

When using small diameter trees as energy wood, technical and economic advantages of "Whole Tree System" are particularly evident, but this method requires the rationalization of the supply chain, since the small size of trees causes low harvesting productivity (Hakkila 1989, Silverides & Sundberg 1989, Spinelli and Verani 2000).

The fundamental condition of the Whole Tree System, when applied to small trees, is the directed tree felling operation, since it will improve work organization, reduce costs and damage risks (Hakkila 1989). So new technical solutions are needed to rationalize small-tree harvesting.

The felling and the contemporary bunching of small trees would increase productivity and biomass recovery (Björheden et al. 2003). But in motor-manual felling, high competence is required, since the chainsaw operator must choice the best felling direction to simplify subsequent skidding, identifying preferential winching lines.

Currently felling and bunching of small trees for chips represents the most expensive work phase in the whole tree system supply chain, whether mechanized or motor-manual performed (Laitila 2008).

When using the traditional short wood motor-manual felling, most of the productive time is spent in tree delimbing, while introducing the full tree system cutting time represents half of the total felling time, since tree delimbing phase is suppressed and the other work phases reduced to a minimum (Hakkila 1989). In whole tree harvesting, a directional felling will address butt ends to the forest trails, allowing a better grip of forwarders cranes or easily connection of chokers placed on cables.

Whether in motor-manual than in mechanized felling the contemporary felling-bunching is an essential passage for subsequent operations, allowing positive economic and silvicultural results (Hakkila 1989). Felling trees with angles of 30-45° to winching lines is ideal when skidding by tractors and winches or cable cranes, reducing possible damages to residual stand. While this angle will be 90° when the subsequent haulage is carried out by forwarders or by tractors equipped with trailers, allowing a better crane grip.

When felling operations are carried out with traditional chainsaw is evident the great ergonomic challenge. These troubles are related to the chainsaw operator work in a bended back position, when cutting trees. Smaller is the tree size and further he assumes this uncomfortable position, pushing chainsaw and guiding the tree falling with one hand, while with the other hand he will support the

chainsaw in an uncomfortable position, increasing exposition to risks and accidents. At the same time the needing to move the fallen tree to a bunch is a cumbersome task.
To minimize these problems during the harvesting of small trees in the Soviet Union chainsaws were fixed to a frame, allowing the operator to remain in upright position during the tree cutting. The same solution was introduced in Finland, developing a working technique for felling and bunching trees with a diameter under 12 cm at stump, using a frame for light chainsaws (Hakkila 1989).
An essential condition of this work technique is the synchronization of the cutting and bunching. Once the stem is severed from the stump, the operator leaves chainsaw resting on the floor and grabs the falling tree with tongs, driving the tree falling by pulling or pushing it, using its kinetic falling energy, moving the butt end to bunches close to a forest trail or a winching line. This technique is simple to learn, but requires adequate training to be performed in the correct manner (Hakkila 1989).
The upright position improves visibility, allowing to plan the subsequent work, essential for an efficient felling process. Ergonomic tests carried out in Czechoslovakia, shown that the frame can significantly reduce operator heart rate, energy consumption, and perceived noise level (Hakkila 1989). Using this advice, the operator should never lift the chainsaw from the ground, getting a better control of trees during falling and guiding to the right bunching direction. However, this advice after the positive results of some tests carried out in Italy in the '80s (Baldini et. al 1989), did not reached large diffusion in our country, while it is widely used in Scandinavian Countries, applying the work methodology actually named "lift -felling "(Laitila 2008).
In order to optimize the whole tree extraction, bunching to the strip road must be integrated with tree felling, since a system based on different machines is usually less efficient from an economic point of view (Hakkila 1989). However if the felling operation is motor-manual, the two working phases are delayed, particularly when working in scattered surfaces, using low technology systems and low trail densities. So the system commonly applied to extract small trees from slope ground is based on the winch cable (average distances of 50 m), usually driven by an agricultural tractor with a power output of 45-60 kW. The use of this machine enables winching of trees for distances inferior to 100 m, however the practice could be difficult when thinning young stands, increasing the possibility of damages to root collars on residual trees (Marchi e Piegai 2001). Furthermore, since the winch cable is manually extended to each tree, a distance increase cause an high physical effort, especially on sloping ground. Therefore, winching productivity increases with greater tree sizes and reducing distances (Fabiano & Piegai 2007, Spinelli et al. 2003). Further, in small tree

winching, the maximum available load is limited by the chokers number and not by the winch pulling capacity (Hakkila 1989).

Trees extraction on slopes over 30%, and distances up to 100 m, can be performed by small cable yarders (Spinelli & Verani 2000, Marchi 1993, Fabiano 1994). Cable yarders allow to work on steep terrain, both uphill and downhill, in areas without adequate roads or forest trails.

Since trees are lifted by a carriage, completely hanged or partially skidded, damage to soil and residual stand is reduced (Lucci 1991). The use of these small cable yarder can be possible through the conversion of farm tractors and winches in small gravity cable yarder lines, based on a small pulley carriage (Marchi 1993). These small cable yarders allow, in part, to reduce drawbacks of heavy yarders, since the easy line installation and therefore the decrease in time losses when the removal reach low or medium intensity. So the system could be practical also in low-intensity harvesting conditions, with little amounts of timber per line (at least 10-15 m^3 for lines with single-span), but the optimal use was suggested from 30 m^3 per line (Marchi 1993). In addition, the small cable yarder allow to reduce economic investment in specialized equipment, having a cost equal to 15% of a mobile tower yarder. However the extraction cost using a cable yarder increase when compared to winches, so the system was restricted to high value timber assortments, and consequently there are few comparisons with winches in small tree extraction.

Small scale technologies are based also on mini tracked tractors with small winches (mini-skidder) and ATVs (Baldini & Spinelli 1990, Nordfjell 1990). In order to use a mini skidder trees are felled with the butt ends on the small machine trailer, so trees are skidded to the forest roads. These machine are driven by an operator walking in front of the machine. The main features are small sizes, low ground pressure and great manoeuvrability. The load capacity reaches 0.3-0.5 m^3, but work distance must remain under 100-150 m, cause their low speed. While the ATVs (All Terrain Vehicle) can be equipped with four-wheel drive, small trailers and a small hydraulic cranes, this equipment permit a payload of 0.5-1 m^3, furthermore these means are faster than a mini skidder.

Once trees are hauled to the forest roads, the next work phase in the energy-wood supply chain is the comminution, this operation can be performed directly at the landing on a forest road, or later at the power station. Typically comminution in Italy is performed at the landing with chippers of great power output (200-300 kW), equipped with hydraulic cranes and mounted on trucks or forwarders (Spinelli and Hartsough 2001). The common storage of large biomass quantities at the landing need the use of medium-high power chippers in order to reach significant productivities. The high hourly cost of this operation forces to reorganize the yards in a logical way, in order to reduce delays, that actually affect the whole supply chain (Cavalli & Grigolato 2007).

"Large scale" harvesting the case of Sweden

A large variety of machines for small tree harvesting was developed since the '70s, each one suited to specific ground and forest conditions.

Two base types of harvester were introduced in felling operations:

- an harvester head directly connected to the frame, so obtaining a machine-tree system, in which the machine move to each tree to be harvested (machine-to-tree method);

- an harvester head is attached to an hydraulic crane, so the crane reaches trees to be harvested, while the vehicle remains on the strip roads (Boom-to-tree method) (Hakkila 1989), these machines became common in the Nordic Countries and in particular in Sweden, reaching the harvester technology as nowadays known.

After the introduction of a single-grip harvester in the early '80s, the profitability of thinning in Sweden radically changed and it became possible to get a profit also from this silvicultural practice (Wallentin 2007). In the ‘90s the dominant scheme became completely mechanized by the two machine system of harvester and forwarder (Nordlund 1996). Trees were selectively felled and processed by an harvester remaining along the strip roads and wood was hauled to roadside by forwarders. Later in first thinning (FT) was introduced the contemporary tree felling and accumulation in bunches, to increase productivity even in small tree harvesting (Björheden et al. 2003). While tree bunching remained a critical problem in small trees harvesting by motor-manual felling system, affecting productivity of subsequent haulage. Since a traditional harvester can not perform more than 120 cycles per hour, felling productivity remains low with small diameters trees, when trees are individually carried to bunches (Hakkila 1989). The bunching time can be reduced using an Accumulating Felling Head (AFH), enabling to cut and accumulate trees together during felling operation (Karha et al. 2006). AFH heads especially designed for energy wood harvesting are not provided of delimbing devices, since trees are not processed (Johansson & Gullberg 2002, Karha et al. 2005). The "multi-tree" system showed to increase productivity by 35-40%, if compared with the traditional system, where trees are individually harvested (Jylhä & Laitila 2007).

Accumulating Felling Head can be mounted on tracked or wheeled machines with rigid or articulated frame. Some harvester machines can be equipped with felling heads with cutting capacity up to 50-60 cm of stump diameter, but these machines are cumbersome in thinning operations and uneconomic in small tree harvesting. Mainly in thinning are needed machines capable of interfacing with delicate silvicultural conditions, affecting with minimal damage soil, roots and residual trees stems (Silverides & Sundberg 1989).

Harvesting machines equipped with a hydraulic crane can operate the felling operation directly from strip roads, reducing possible soil compaction and roots damage, so the length of the crane determines the strip road spacing. The machine productivity is influenced by a number of factors related to different harvesting conditions including: tree size and branchiness, undergrowth vegetation, stand fertility, residual stand density, spacing of strip roads. (Eliasson 1998, Karha et al. 2005). Thinning harvester can reach productivities up to 11-13 m^3/h, harvesting small trees with stem volumes of 30-40 dm^3 (Karha et al. 2006). Furthermore, the ability of hydraulic cranes to move trees for longer distances than in motor-manual felling allows to create larger bunches and finest located for a subsequent haulage (Laitila et al. 2007).

However, harvesters are often expensive in immature stands operations, since the productivity of mechanized methods is strongly related to tree size (Silverides & Sundberg 1989; Karha et al. 2006).

Moreover physical and economic complications limited the use of these machines on steeper terrain conditions (slope over 30%), however new models were developed able to operate on slopes up to 60%, through the use of special cabins with levelling platforms and low centre of gravity or equipped with telescopic stabilizers (Spinelli & Stampfer 2002).

The subsequent haulage from strip roads to the landings in large scale harvesting is usually performed by frame articulated tractors named forwarders, so trees are loaded on forwarder with hydraulic cranes, reaching bunches up to 10 m from the strip roads. These machines are characterized by weights of 11-13 tonnes, payload of 10-12 tonnes, equipped with 6-8 wheel drive, but are just 2.7 m in width (Laitila et al 2007), so able to pass in corridors of only 4 m.

In large scale energy wood supply chain the comminution is the central element, since it determines the form of material for subsequent road transportation (Hakkila 2003). In Sweden, this operation is usually performed at roadside, during periods of higher chips demand, during the winter season, after a natural tree seasoning, so after a moisture content reduction and contemporary increase of the chips calorific value (Berg 2003).

From the economic point of view felling and bunching represent the largest supply chain costs (Laitila 2008, Karha et al. 2005). Therefore, to reach a sustainable use of chips, the felling costs should be minimized and biomass removal maximized, so whole trees are harvested and chipped. However the introduction of the whole trees harvesting could reduce future stand growth, due to nutrients losses, generating economic and ecological consequences (Jylhä 2004), so strategies to contain the loss of nutrients and guarantee the sustainability of these practices must be identified. At the same time proper technologies are still needed in thinning practices, in order to reduce the immediate impacts, such as increased soil compaction and residual trees damages.

OBJECTIVE

The study analyzes whole tree system introduction in small diameter energy wood harvesting with small scale mechanization in Italy. The different studies carried out in Italy included thinning of conifer plantations, coppice cutting, post fire logging and short rotation plantations (SRC) harvesting.

Field studies analyzed different small scale technologies, in order to give suggestion for future harvesting equipment choice in different silvicultural conditions.

At the same time whole tree system is analyzed in large scale harvesting, through results of a field study and theoretical simulation carried out in Sweden, comparing traditional pulpwood thinning to energy wood harvesting systems in young stands thinning.

The main factor affecting small tree felling and extraction will be analyzed, in order to maximize productivity, reduce damage to residual stand and improve ergonomics and economic sustainability.

Using data from field studies, time consumption models will be developed, for different harvesting machines and conditions, in order to address future harvesting simulations.

The study will finally provide biomass potential in the different operational contexts, small tree harvesting costs and related CO_2 emissions.

MATERIAL AND METHODS

The productivity analysis in forest harvesting

The aim of a productivity study is to identify the average time consumption in a work cycle to obtain a wood product (Harstela 1991). The detailed survey of work times is performed by dividing the operating cycle in sequential time elements, whose duration depends on the specific work task and characteristics, so it is possible to establish the relationship between productivity and working conditions and create a statistically valid prediction model (Olsen et al. 1998).

The work time analysis can be performed through a comparison of different work methods and a study of detectable correlations. The work time sampling can be made by measuring the time in continuous or through a sampling of the work elements by regular time intervals. Direct working time measurement requires a researcher with appropriate experience and elements of sufficient length to be measured (Olsen et al. 1998).

The analysis of working time allows to identify factors affecting time variability and to extrapolate existing regressions. The comparison of two models can be performed by the introduction of the same value for the same investigated variables.

If the study aims to compare productivity differences for different harvesting methods specific measures can be used to minimize unwanted variability, in particular:

- Measurement of all relevant variables (eg. diameters, distances)
- Measurement of delays
- Detailed survey for a sufficient time span.

The removal of unwanted variability associated with not quantifiable variables and delays can help to reach the objective of effective productivity analysis.

Unexpected variables that could affect productivity are:

- Not measurable conditions
- Delays occurrence.

The sources of variability to be excluded from the comparison include:

- Level of operator training: (education, learning, attitude)
- Level of motivation
- Man-machine compatibility
- Operator coordination
- Type of remuneration
- Machine and equipment not suited to the specific work objective
- Weather conditions.

Ideally, all these factors should be standardized, that is possible by using the same equipment and the same operator in different work systems comparison. Moreover a sufficient training time will be needed for different systems to achieve the same levels of experience.

A long period survey (follow up study) allows to quantify long-term productivity and salaries, since allowing a proper sampling of delays, contributing to an evaluation of total work time, but usually these studies are limited to general operations descriptions, without a detailed measurement of variables that can influence work times.

Since money and time are limited resources, the researchers must decide how to apply different sampling methods.

In particular, the detailed sampling will be used to compare the effective productivity (t/E_0h) for different work methodologies, recording also the short delays occurrence, with extension inferior to 15 minutes (E_{15}h), however long delays will not be sufficiently sampled, since these could occur rarely.

The work time sampling, for different harvesting systems, should be carried out randomly, so the unexpected variability will be randomly distributed on the different work alternatives.

Statistical tests may be useful to notice significant differences in time study results, measuring the standard error (S.E.) associated to each sample. So a difference in average work cycle will be considered significant if exceeding the standard error recorded during time studies (Olsen et al. 1998).

The analysis of greenhouse gases emissions in forest biomass harvesting

The combustion of forest biomass for energy production is considered a "neutral" practice, since the amount of CO_2 fixed by trees growth is released during wood combustion. While fossil fuels combustion cause the emission of CO_2 fixed in millions of years. Thus biomass reaches a closed CO_2 cycle, except greenhouse gases (GHG) released in production, harvesting and transportation.

Among tools to quantify these emissions LCA (Life Cycle Assessment) found considerable application, in accordance with international reference protocols (ISO 14040). This approach is based on energy and environmental balances in production and use of particular products.

Therefore, in this study were analyzed CO_2 emissions using a LCI (Life Cycle Inventory), considering biomass harvesting in small-scale operations in Italy.

In our study the inventory boundaries included emissions implied in biomass cutting and forest transportation per MWh (3600MJ) of energy. In emission calculations were considered fossil fuel used in processes of biomass harvesting, the corresponding emissions were obtained from national emission inventories (ANPA 2002), these were added to fuels and lubricants production (gasoline, diesel, mineral oil lubricants) (ANPA 2002; Athanassiadis 2000) and machines production (Börjesson 1996), emissions were converted into KgCO2eq., according to the GWP (IPCC 1996-100 year time horizon) . The calorific value of biomass in each site was obtained through laboratory tests using a calorimeter (Mahler bomb). The consumption of fuels was measured, weighing fuel bins used in forest operations, while lubricant consumption was calculated by literature (Heller et al. 2003), and the corresponding energy content were derived from Pimentel (1980).

STUDY I

Materials and methods

The first study was carried out in young maritime pine stand (*Pinus pinaster* Aiton), 18 years old, damaged by a wildifire in August 2005, located along the Tuscany coast in the municipality of Calambrone, near the town of Pisa (43°35' N, 10°17'E), the study area was included in the perimeter of the Regional Park St. Rossore Migliarino Massaciuccoli. The forest was located on a flat ground (I class of slope), with little terrain roughness, the site was accessible by a developed network of roads and forest trails.

A post fire clear cut was carried out by whole tree harvesting system, allowing new seedlings to grow and removing possible fire baits. In this stand were compared two harvesting methodologies based on the whole tree system. The field study started in summer 2006 and ended the same year in the winter season. Trees were motor-manually felled by a light chainsaw and directed with the butt ends to a forest trail, then trees were winched to the trail by a wheeled farm tractor equipped with a forest winch, then chipped as energy wood.

In directed tree felling operation were compared two work methodologies, the evaluation was carried out in a work area of 1ha, the study surface was divided into two homogeneous plots of 0.5 ha. In plot 1 the felling operation was performed with a traditional chainsaw (Figure 1), while in plot 2 the same operation was performed using the same chainsaw with felling frame (Figure 1). The operations were carried out by a two operators crew, a person using the chainsaw, the other guiding tree falling and contemporary bunching, moving the butts ends to the winching lines. The two different felling methodologies were performed by the same crew. Operators were trained for a short period (three hours) in each work methodology, since they had no previous experience in felling frame use. The same chainsaws (STIHL 025 2.3 kW) was used in the entire field study. During the felling operation all felled trees were counted, so post fire density was calculated. On a sample of 125 trees, randomly extracted every day at the end of felling operations, were measured diameter at stump, height and diameter at middle height. The volume of each sample tree was calculated using diameter at middle height and total height, applying the cylinder formula. Branches and needles were not measured, since partially burned during the wildfire. On a sub-sample of 10 trees were collected three discs, one from tree base, one from middle-height and one from the top, the discs were weighed and measured with a calliper to calculate volume, these data were used for the calculation of the gravimetric fresh density, the value obtained was used to convert volumes into weight, the same discs were dried in a stove at 103°C, determining the fresh material moisture content (UNI 9091/2). The other dendrometric features were obtained from results of another research group, working in the same area. (Project PRIN-MIUR 2005) (Giovannini & Marchi 2009).

During the felling operation was carried out an analytic survey with a continuous recording of working times, using two centesimal stopwatch chronometers and a totalizer. In time recording analysis effective time (E_0h) of each work cycle was divided into time elements. At the same time were recorded delays shorter than 15 minutes in order to calculate the gross work time (E_{15}h). Time study had a total length of 10 hours for each work methodology.

In net time (E_0h) recording the work cycle was divided in the following time elements (same time elements were used in the two areas Plot 1 and Plot 2):

Passage: time between the end of a cutting operation on a tree and the beginning of cutting phase on next tree.

Cutting: time between the start of a cutting process on a tree and its complete detachment from the stump.

Accessory: other times required by the main work (eg. bunching, stump trimming).

Figure 1: Directed felling operation by traditional chainsaw (on the left) and by chainsaw with felling frame (on the right). Different operator postures can be noted.

The recorded effective time was divided into hourly sessions, for each felling methodology, in order to compare the hourly effective productivity, given by the ratio of product (N. trees, t, o.d. t) and effective work time (E_0h).

Effective times and effective productivities achieved in the two methods were compared by one-way ANOVA statistical analysis ($p < 0.05$) to find significant differences.

Delays were used to quantify the conversion of effective productivity in gross productivity ($E_{15}h$) for each felling method.

At the end of felling operation 50 stumps per plot were selected according to a randomized sampling scheme and cutting surface height was measured. The measurements were used to find significant difference between felling methods through T-test ($p < 0.05$).

At the end of felling, trees were winched to forest trail by a farm tractor (FIAT 780 DT 52 kW) equipped with a forest winch (KRPAN 4t) (Figure 2) with 11mm diameter and 80m length cable. Trees previously arranged in bunches were fastened by chains, using choker hooks coupled on winch cable, so trees were winched the forest trail. The operation was carried out by a two operators crew, the first operator fastened bunches to winch cable and the second operated winch and tractor controls.

During the winching operations was carried out a detailed and continuous time recording on the whole harvested surface of 1 ha, analyzing effective work time (E_0h) and gross time including short time delays ($E_{15}h$).

The effective work time was divided into the following work elements:

Cable extension: time between cable release from the winch drum and its extension to the farther bunch.

Load connection: time between the complete cable extension to complete connection of tree bunches to the winch cable.

Winching: time between the beginning of cable pulling to complete load extraction to the winch blade.

Load unfastening: time between the release of the cable from the winch drum to complete load unfastening.

Accessory: other necessary times (eg. tractor manoeuvring, load adjustment).

Figure 2: Whole tree winching operated by farm tractor equipped with forest winch

In addition were measured variables affecting each winching cycle including:

- Winching distance
- Tree number.

The effective work productivity was obtained by the ratio of load (number of trees multiplied by weight) and the effective cycle time (E_0h).

Analysis of effective cycle time allowed to find significant relations between work times and measured variables, calculating linear regressions, using variables significantly ($p <0.05$) affecting each work element, so creating an additive model for effective time calculations.

Based on gross productivity, resulted in the field study, completed by literature gross productivity coefficient, using Hippoliti (1997) formula were calculated hourly machines costs. In cost calculations was considered a value of 700 € for the light chainsaw with felling frame and 43.000 € for the wheeled farm tractor with forest winch. Assuming a lifespan of 2.000 hours for the chainsaw and 10.000 hours for the wheeled farm tractor (Hippoliti 1997). Machine costs were added to labour cost, derived from national contracts. So were calculated the whole tree harvesting and extraction (to roadside) costs.

Results

Table 1 shows stand and mean harvested tree characteristics, obtained from collected data. The pine forest was of high density, since previously were not carried out thinning or cleaning practices.

The low moisture content of fresh material was caused by fire passage, furthermore a part of needles were burned, so this component was not included in removal calculations.

Table 1: Stand and average tree characteristics.

Density (Tree ha^{-1})	4650
dbh (cm)	7.5
Stump diameter (cm)	9.2
Height (m)	7.4
Stem volume (dm^3)	21
Total stem volume (m^3 ha^{-1})	97.8
Stem mass (kg)	10.2
Misture content (%)	14
Stem dry mass (o.d. kg)	8.8
Total stem mass (o.d. t ha^{-1})	40.9

From single tree mass was calculated the stem biomass (o.d. t) for different diameters (dbh) (Fig. 3), this information is particularly useful for biomass removal calculations in silvicultural treatment of young Mediterranean forests (eg. first thinning).

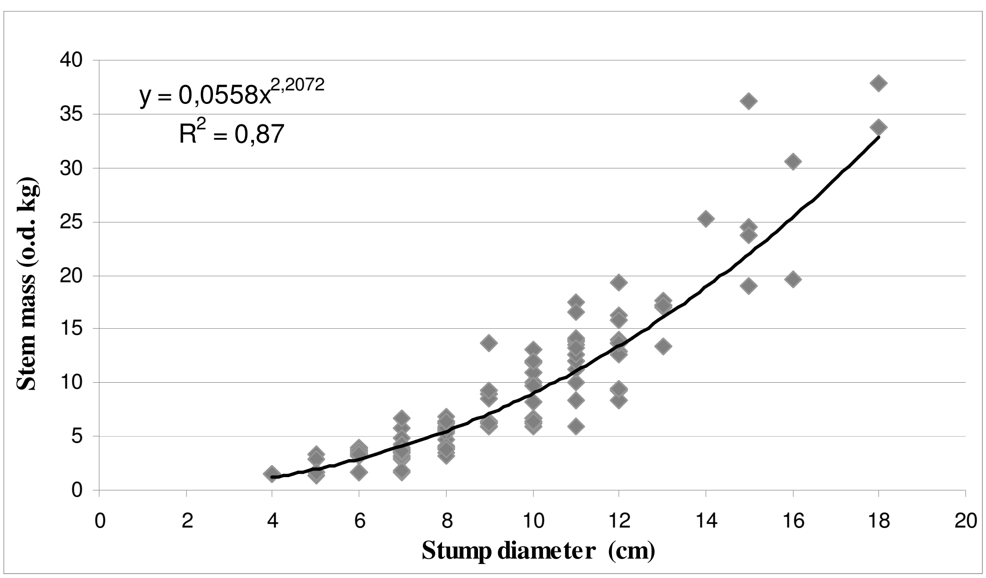

Figure 3: Stem dry mass as function of tree stump diameter

Analysis of felling times (Table 2) underlined an increase of effective cycle time with the felling frame, that was particularly determined by a significant increase of cutting time, resulting from difficulties in cutting trees with a stump diameter exceeding 15 cm. Moreover with the introduction of the felling frame was recorded an increase of accessory times. However felling frame allowed a reduction of passage time, so more trees were cut from the same machine location.

Table 2. Effective time elements in felling operation (cmin), two operators crew, standard deviation between parenthesis, different letters in each row show significant difference ($p<0.05$).

	Time per tree		Effective time percentage	
	Chainsaw cmin (s.d.)	Felling frame cmin (s.d.)	Chainsaw	Felling frame
Passage	10.0 (3.1)a	7.6 (3.1)a	32.9%	20.8%
Cutting	10.6 (2.3)a	16.8 (3.9)b	34.9%	45.9%
Accessory	9.8 (5.2)a	12.2 (3.3)a	32.2%	33.4%
Effective time (E_0h)	30.4(8.3)a	39.0 (6.3)a		

So traditional chainsaw methodology achieved an effective productivity 24% higher than chainsaw with felling frame (Table 3), however the productivities were not significantly different ($p> 0.05$). Delay analysis showed a gross time ($E_{15}h$) percentage of 14% with traditional saw and 6.2% with felling frame, that difference was mainly due to the chainsaw operator pauses (+30%), so the productivity gap between the gross productivities was reduced to 16%.

Table 3. Effective productivity per different felling methodologies, two operators crew.

	Chainsaw	Felling frame	Pr > t
Trees/E_0h	210	169	0.055
t/E_0h	2.2	1.7	0.055
o.d.t/E_0h	1.9	1.5	0.055

In the analysis on stump height after tree felling (Fig. 4) was noticed a significant difference between the two plots, the average stump height decreased from 7.2 cm (felling frame plot) to 4.3 cm (traditional chainsaw plot), furthermore in felling frame area was recorded a reduction of cutting surface slope.

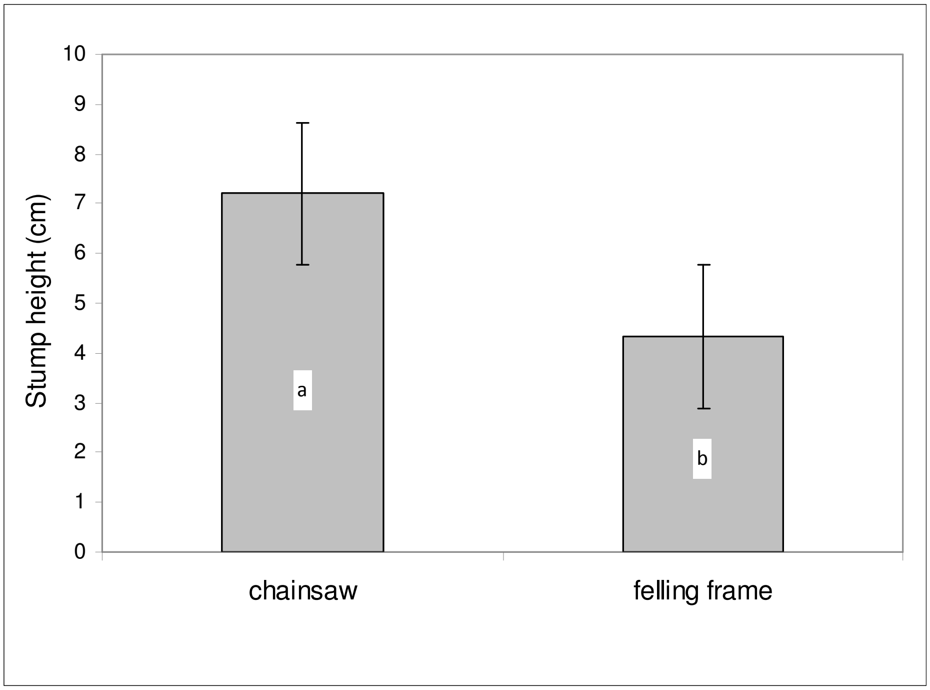

Figure 4: Stump height per felling methodology, different letterers are used for significant differences ($p<0.05$), lines indicate standard errors.

Analysis of winching operation, on 104 work cycles allowed to calculate main work elements (Table 4). The results pointed out an high incidence of load connection times, since the difficulties in passing chains under small trees bunches, the result was a small number of trees in each load, so pulling force was not completely used, thus generating a low effective productivity. Analysis of delays showed a low incidence on total time (Table 4), mainly due to load adjustment.

Table 4: Winching effective time elements (cmin), effective time percentages (E_0h), yard average features (variation interval) and effective productivity.

Cable extension (cmin)	74.5	11%
Load connection (cmin)	282.5	43%
Winching (cmin)	82.1	13%
Load unfastening (cmin)	123.1	14%
Accessory (cmin)	91.0	19%
Effective time (E_0h) (cmin)	653.2	
Delays (% $E_{15}h$)	10%	
Operator (n)	2	
Distance (m)	17 (5-35)	
Load (Tree N.)	17 (6-35)	
Load (o.d. t)	0.17 (0.06-0.36)	
Effective productivity (t/h)	1.6	
Effective productivity (o.d.t/h)	1.4	

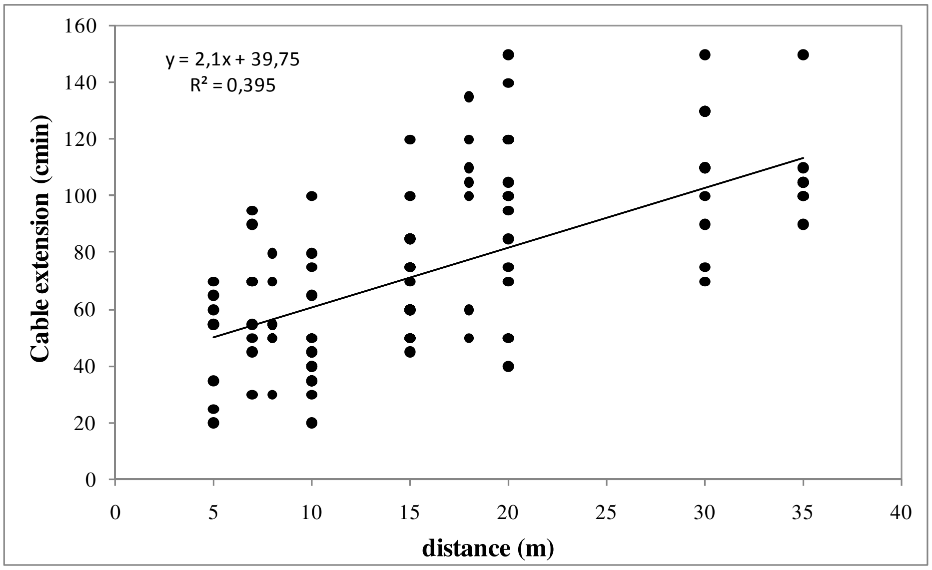

Figure 5: Cable extension time (cmin) as function of winching distance(m).

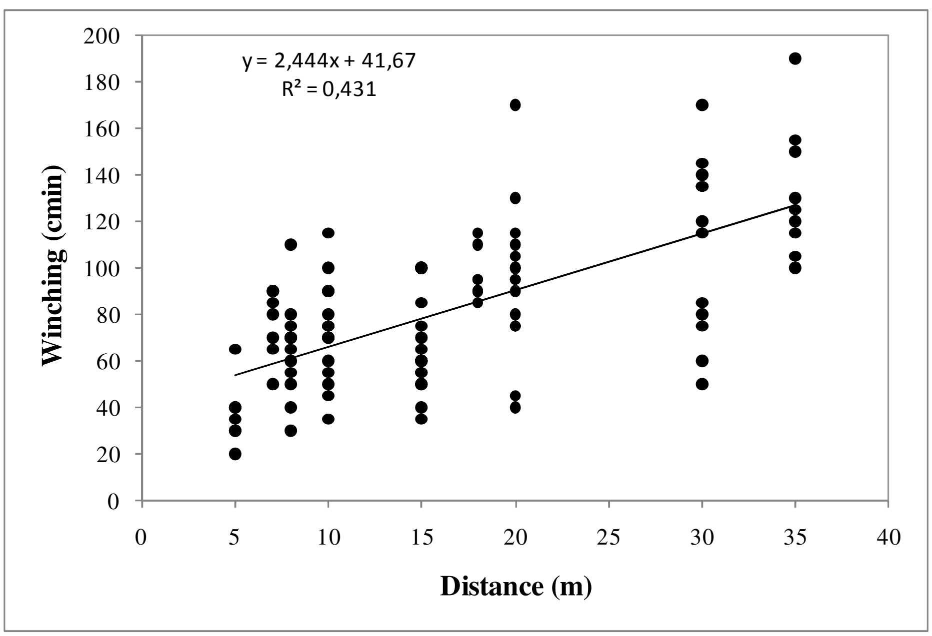

Figure 6: Winching time (cmin) as function of winching distance(m).

The analysis of measured variables showed a correlation between distances and cable extension and winching time elements (Table 5). At the same time there were not significant correlations between number of trees and work times, so it was possible to increase load without affecting work time. These results allowed to create a model for effective time calculations, based on winching distances.

Tabella 5. Effective time per cycle (E_0h) (cmin) linear regression model in winching by farm tractor and forest winch.

T= Effective time (cmin)			
T=T1+T2+T3+T4+T5			
Cable extension	Coefficient	Pr > t	R^2
T1= 39.752 + (a)*dist			0.395
a	2.100	< 0.0001	
T2=Load connection			
Constant	282		
Winching			
T3 = 41.674+ (b)*dist			0.431
b	2.444	< 0.0001	
T4=Load unfastening			
Constant	123		
T5= Accessory			
Constant	91		
dist= distance (m)			

Discussion

In the study was not possible to appraise the total biomass amount, since tree crown were not measured, however was obtained a model allowing to calculate the stem biomass for trees with a stump diameters from 4 to 18 cm, allowing to estimate the biomass potential in first thinning of young Mediterranean pine forests.

The stem biomass function obtained from this study can be integrated with the crown biomass equations reported by Baldini et al. (1989), extrapolated in *Pinus pinaster* stands, grown under the similar management conditions. So considering in the found equation the average stand diameter (7.5 cm Dbh) and using Baldini equations for crown mass calculations, whole tree mass removal resulted 24.5% superior to stem mass. Therefore results of this study, integrated with Baldini et al.

(1989) allow to calculate stem mass obtained in different stand conditions and for different harvesting practices in Mediterranean pine forests.

The felling frame did not allowed to significantly increase the effective work productivity, if compared to traditional chainsaw, however it reduced the percentage of delays included in E_{15}h, the reduction could be explained by a lower chainsaw operator effort, as suggested by other studies (Baldini et al. 2002). The study of Baldini et al. (1989) in a first thinning ,carried out in a similar stand, where a two operators crew used a felling frame, with a remaining stand density of 2000 trees/ha, showed a 40% increase in gross productivity, if compared to traditional chainsaw. So results obtained with the felling frame in our study seems to be influenced by cutting difficulties, when stump diameter was superior to the average tree, since performing a clear cutting operation. As the chainsaw with felling frame realized a cut parallel to the ground surface, the chink tended to close if trees were larger than 15 cm, stopping the saw chain progression, so overheating the saw bar and jeopardizing subsequent felling work.

As suggested by Ihonen (1998) when using felling frame technique the operator remains with a free hand useful to push the tree fall in a chosen direction. So the choice of the two operators crew interfered with the identification of possible differences in felling times, since tree falling was directed by the second operator. Baldini et al. (1989) demonstrated in their study that one operator crew maximizes productivity if compared to the two operators crew, therefore it would be more appropriate to use this crew in time study comparisons, unfortunately this was not possible in our study, since the public administration provided the operators only for a limited number of days, so they were arranged in crew of at least two persons.

A field study performed in Maine (USA) showed that felling frame allows to improve motor manual felling productivity, especially on conifer forests, characterized by a narrow cylindrical crown shape. In the American study, carried out in a dense fir stand, was achieved a productivity of 109 trees/E_{15}h with diameters of 10 cm, so these results were in line with our study (Hakkila 1989). In Finland the felling frame working method resulted highly efficient, especially when harvesting small sized pines and birches, but the frame use did not resulted high productive in spruce stands, since the long and heavy crowns hindered the correct felling direction. In field studies performed in Germany, harvesting young conifer stands, the productivity achieved with the frame did not differed significantly from traditional chainsaw, but the ergonomic advantages recommended the frame use (Hakkila 1989).

In our study the felling frame allowed to obtain also a significant reduction of stump heights. This result could allow a possible reduction of delays occurrence during winching operations; since in winching phase the lower stump heights allow to reduce pulling collisions, so increasing gross work productivity. Moreover the lower stump height cold reduce tires punctures in the case of stand chipping with wheeled tractors, especially in Italy, where vehicles used in forest operations are often derived from farm tractor, so using tires not suitable for forest activities. At the same time a reduction of stump height allows an higher biomass removal, otherwise remaining on the stump. Furthermore, in the case of coppice hardwood cutting the stump height reduction will enhance following stand sprouting.

The number of trees per winching cycle was not correlated with working time. Consequently the model showed that it was possible to increase productivity by increasing the number of trees per load, without affecting working time. The same effect appeared in other winching conditions (Spinelli et al. 2003) in small trees logging. In the study of Baldini et al. (1989), winching an average of two bunches per cycle, resulted an average load of 0.28 t, while in our case winching only one bunch per cycle the average load resulted of 0.17 t; in our study the chocker hooks on the winch cable were rarely used and trees fastened directly using winch cable, without the use of chains to form bunches. This resulted in gross winching productivity 20% lower than values reported by Baldini et al. 1989.

From economic assumptions and field study productivities were calculated costs of whole tree felling and extraction at the forest trail in €/t. The costs were expressed as €/t, since current energy wood market in Italy is based on a price for fresh material. In cost calculations was included felling productivity of chainsaw with felling frame, considered nowadays the best felling method in similar conditions and assuming the average winching distance resulted in the field study. Assuming a 10% incidence of delays in felling operation and 10% in winching, so considering reliable delays incidence occurred in the field study and assuming two operators crews for both operations. From these assumptions resulted costs shown in Table 6.

Under current market conditions, the price for energy wood chips at forest trail can be assumed 35 €/t, if we consider a comminution cost of 12 €/t (Magagnotti et al. 2009), the price of the whole trees at forest trails results 23 €/t. The difference of whole trees price and costs in Table 6 gives a negative balance of -28 €/t.

Table 6: Operation cost resulted in the field study

	Hourly machine cost	Hourly labour cost	Operation cost	Gross productivity	Total cost	Percentage of total cost
	[€ h^{-1}]	[€ h^{-1}]	[€ h^{-1}]	[t h^{-1}]	[€ t^{-1}]	[%]
Felling	2,87	30,00 (2)	32,87	1,73	19,03	37%
Winching	16,44	30,00 (2)	46,44	1,45	31,93	63%
Total					**50,96**	

( ) Number of operators

If we assume the same productivity in terms of trees/E_{15}h, but considering green tree harvesting (eg. geometric thinning), productivity in term of mass could be 25% higher than in the field study (to include crown mass), at the same time another 30% increase could be assumed to consider the moisture content of fresh material. In this hypothetical harvesting condition energy wood cost results as in Table 7. Even in this case economic sustainability is not reached, but losses are considerably reduced.

Table 7: Operation costs in case of whole tree harvesting

	Hourly machine cost	Hourly labour cost	Operation cost	Gross productivity	Total cost
	[€ h^{-1}]	[€ h^{-1}]	[€ h^{-1}]	[t h^{-1}]	[€ t^{-1}s.f]
Felling	2,87	30,00 (2)	32,87	2,68	12,28
Winching	16,44	30,00 (2)	46,44	2,25	20,60
Total					**32,88**

( ) Number of operators

Based on machine masses, fuel consumption recorded in the study and calculated lubricant consumption was carried out an inventory of CO_2 emissions during harvesting operations as in Table 8.

Table 8: Kg Co2 eq. /MWh emissions resulted in the field study.

		Direct emission	Indirect emission		Total emission	
			Fuel production	Machine production		
Chainsaw and felling frame	Mixture	0,31	0,01	0,001	0,34	12%
	Lubricant		0,02			
Farm tractor and forest winch	Diesel	2,01	0,08	0,438	2,55	88%
	Lubricant		0,02			
%		80%	20%		2,89	

STUDY II

Material and methods

The second study was carried out through a post fire cutting in a downy oak (*Quercus* pubescens Willd.) coppice stand, 20 years old, damaged by wildfire passage in July 2005, the stand was located in the municipality of Umbertide (PG) (43 ° 17'N, 12 ° 22'E), Umbria Region. A forest trail was positioned on the top of the cutting surface. The stand was located on a 45% average ground slope (class III), characterized by high roughness, created by rock steps and several boulders. The time study was carried out in the autumn 2006, at the felling time many new sprouts were shooting from oak and ash stumps. In the study was used the whole tree harvesting system, in order to simplify wood extraction, remove all potential fire baits and to allow motor-manual processing in a safer work condition. Trees were felled motor-manually by chainsaw, then winched uphill to the forest trail, comparing two different extraction systems based on forest winches. So trees were converted into chips using a small tractor driven chipper.

The post fire stand dendrometric measures were obtained by the support of another research unit working in the same area (Giovannini & Marchi 2009). Measurements were integrated by sampling of 105 felled trees, measured in diameter at stump, diameter at middle height and total stem height, so stem volume was calculated by the cylinder formula. Successively 10 trees with average stump diameter were selected from the total study surface and stem and branches (diameter inferior to 3cm) were weighed on a certified scale. So the average incidence of branches on total mass was calculated, in this calculation were not included leaves, since this component was lost after the fire passage. On a sample of five stems were collected discs from base, middle height and stem top; these discs were weighed and measured with a calliper to calculate volume, so used in fresh density calculations, the same discs were dried in stove at 103°C, determining the biomass moisture content (UNI 9091/2). Stem volumes were converted into fresh weights, using the calculated stem density, so branches mass was added, obtaining the total average tree mass.

The directed tree felling was performed by a two operators crew (Fig. 1).. While an operator used the chainsaw in tree cutting, the second guided trees in a directional falling, arranging bunches with butt ends pointed to the forest trail. Tree felling was performed with a light chainsaw (STIHL 026 2.6 kW). During the felling operation was carried out a detailed work time recording on a total surface of 1.75 ha, recording the effective work time (E_0h) and short delays (included in E_{15}h), the time study measurement lasted ten days.

From productivity calculation were excluded time related to seed trees felling and extraction, since the productivity study was addressed to small size tree harvesting.

In effective time (E_0h) recording the work cycle was divided in the following time elements:
Passage: time between the conclusion of a cutting process on a stump and the beginning of cleaning operation.
Cleaning: time required to clean a stump with chainsaw, removing herbaceous and shrub vegetation hindering cutting operation.
Cutting: time between the beginning of cutting operation on the first tree to complete severing of last tree on the stump.
Accessory: other times necessary in the effective work (eg. bunching, stump trimming).
During the operation was counted the number of stem on each harvested stump.

Figure 1: Motor-manual felling operation performed by a two operators crew with a light chainsaw

At the end of felling operation the total stand area was divided in two adjacent sub areas, to compare two different extraction methods, using the same base machine (a forest winch).
In the first sub-area of 4000 m^2 tree extraction was performed by a forest winch, powered by a farm tractor; while in the adjacent area of 2500 m^2 was used a light cable yarder, using as mainline the forest winch cable (Fig. 2).
In the first sub-area tree winching was performed using a tracked farm tractor (TL LANDINI C / C 8860, 61 kW) equipped with forest winch (TERRMACCH V6000/8000, pulling force 60 kN) with 12 mm diameter and 80 m length cable. The winching operation was carried out by a three operators crew, of which two fastening bunches to winch cable using chains and choker hooks and the third operating winch and tractor controls.
During the winching operation was carried out a detailed continuous time recording on the total harvested surface, analyzing effective work time (E_0h) and gross time including short delays ($E_{15}h$).
The effective work time was divided into the following work elements:

Cable extension: time between the cable release from the winch drum and its extension to the further bunch to be winched.

Load connection: time between the cable complete extension to the complete coupling of all bunches to be winched.

Winching: time between the beginning of cable pulling to concentration of trees to the winch blade.

Load unfastening: time between the cable release from the winch drum to complete load unfastening.

Accessory: other necessary times (eg. tractor manoeuvring, load adjustment).

In the adjacent area of 2500 m^2 was installed a light gravity cable yarder (with MAXWALD carriage, 800 kg payload). The carriage was driven by the same tractor and the same winch used in the winching operation. So the winch cable was used as mainline to uphill tree yarding, while a second cable with a diameter of 12 mm was tensioned between two spar trees and used as skyline (Fig. 3). The cable yarder was operated by the same three operator crew formerly winching trees in the adjacent area. So an operator remained at the landing using tractor and winch controls, while two operators were fixing bunches with chains to the carriage hook. Tree bunches were firstly concentrated under the skyline by carriage hook, so butt ends were lifted from the ground and yarded to the landing, where the carriage was unloaded.

The operators were experienced in winching operations, trained on cable yarder use but without long time work experience.

Carriage out: time required by the carriage to move from landing to the valley block

Loading: time required from the release of carriage hook to the complete load coupling

Carriage return: time required to extract the load to the landing block

Unloading: time required to completely unload trees bunches from carriage hook

Accessory times: other times related to effective work time (eg. moving the valley block, communication between the operators).

In addition to the work time recording were measured variables affecting each work cycle, measuring:

- Extraction distance
- Number of trees per load.

The effective work productivity was obtained from the ratio of load (number of trees multiplied by average tree weight) and the effective work time.

During the study was carried out a measurement of short delays, to calculate the gross time conversions ($E_{15}h$).

In the cable yarding study were recorded also times needed for line installation and disassembling, this operation was performed by three skilled operators.
Effective time analysis allowed to find significant associations between work times and measured variables and to calculate linear regressions significantly ($p < 0.05$) affecting each work element, creating an additive model for effective time calculation in forest winching and small cable yarder whole tree extraction.

Figure 2: Comparison of winching (on the left) and small cable yarder extraction (on the right).

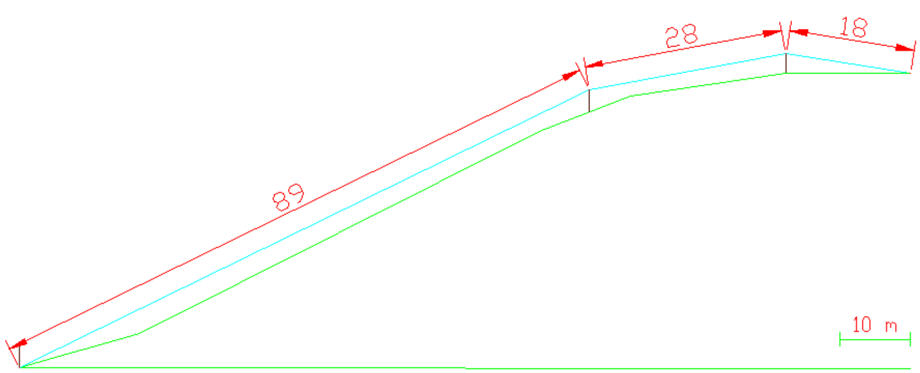

Figure 3: Small gravity cable yarder terrain profile (green) and unloaded theoretical skyline (blue).

Based on gross working productivity, resulted by time study, integrated by literature coefficients, using Hippoliti (1997) formula were calculated hourly machines costs. In cost calculation was considered a value of 500 € for a light chainsaw, 38.000 € for a tracked farm tractor with forest winch and 6.700 € for the other small cable yarder components. Assuming a useful lifespan of 2.000 hours for the chainsaw, 10.000 hours for the farm tractor and 2.500 hours for other cable yarder components (Hippoliti 1997). Machine costs were added to labour costs, derived from national contracts. So felling and extraction (to roadside) costs were calculated.

Results

The main characteristics of stand and average tree harvested during the study are shown in Table 1. From tree masses sampling resulted an incidence of branches (diameter lower than 3 cm) of 31 % on total tree fresh biomass. The stem mass measurements were used to calculate the regression of total stem biomass in function of stump diameter (Fig.4).

Table 1: Stand and average tree characteristics.

Density (Trees ha^{-1})	2940
Density (Trees ha^{-1})	1185
dbh (cm)	7.5
Stump diameter (cm)	9.7
Height (m)	6.4
Stem volume (dm^3)	17
Total stem volume (m^3 ha^{-1})	50.0
Stem mass (kg)	15.2
Tree mass (kg)	22.0
Moisture content (%)	24
Tree dry mass (o.d. kg)	16.7
Total dry mass (o.d. t ha^{-1})	49.1

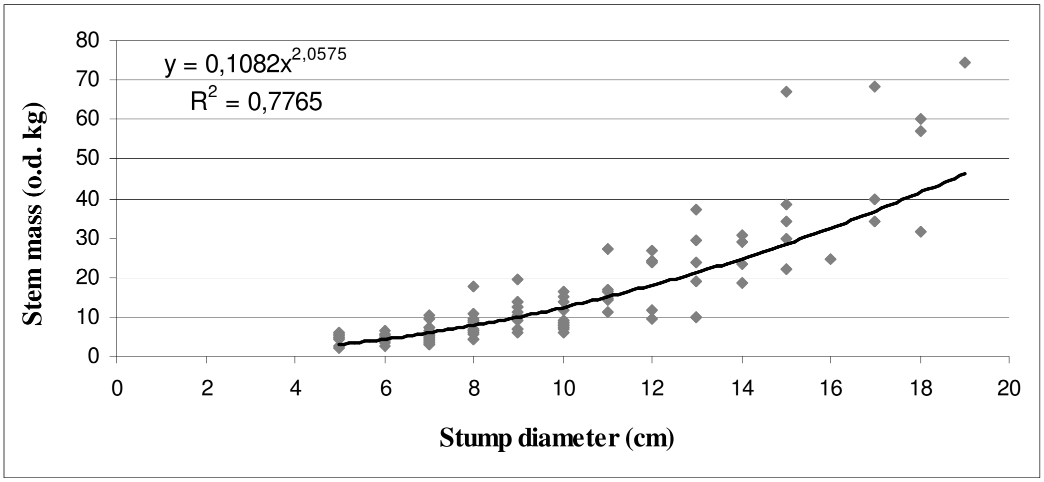

Figure 4: Stem dry mass in function of sample tree diameter at stump.

The analysis of effective felling times per stump (Table 2) underlined the strong incidence of accessory times, indispensable to correctly direct tree falling and bunching during felling operation, since the stem position on stumps caused different natural falling directions. Moreover, the effective time was increased by the cutting blade overheating, since the machine was used to cut dry hardwood.

Table 2. Felling time elements per stump (cmin), effective time percentages and effective productivity.

	Time per stump cmin (s.d.)	Time percentage
Passage	47.4 (14.5)	30.0%
Cleaning	18.0 (7.5)	11.4%
Cutting	58.3 (26.3)	37.0%
Accessory	34.0 (18.1)	21.6%
Effective time (E_0h)	157.8 (29.9)	
Effective productivity (Stem/E_0h)	93	
Effective productivity (t /E_0h)	2.1	
Effective productivity (o.d.t/E_0h)	1.6	

Time delays included in $E_{15}h$ showed an incidence of 19.7% on total time, due to several interruptions for machine lubrications problems and operators pauses.

The subsequent analysis of working time elements pointed out a significant and strong correlation between number of stem per stump and cutting time (p <0.0001), this correlation could be used in a linear model regression to calculate the effective felling time per stump (Table 3).

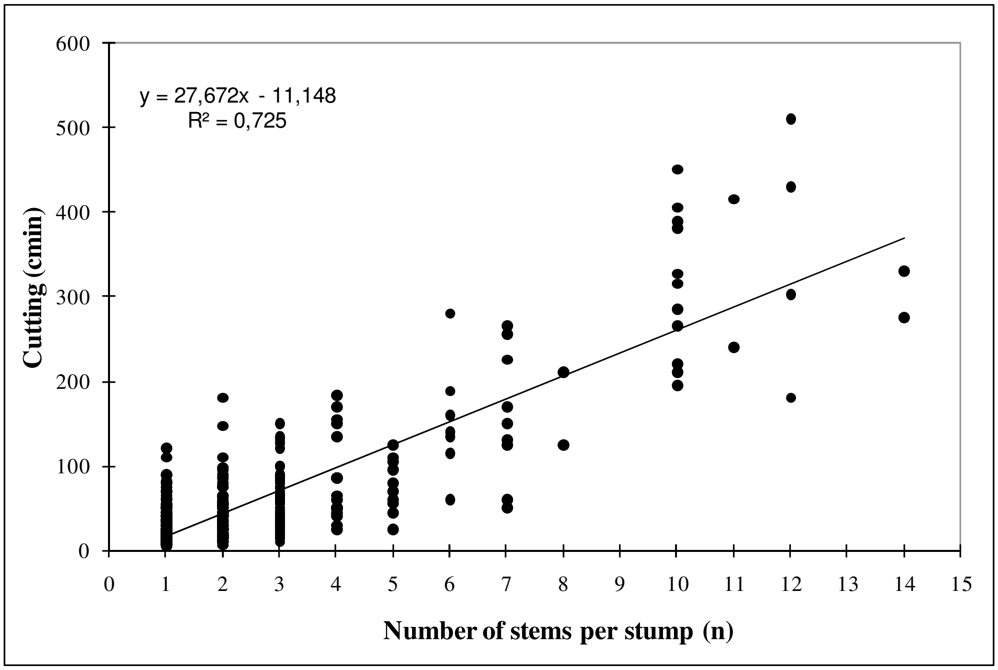

Figure 5: Cutting time regression as function of trees per stump

Table 3. Felling effective time per stump (E_0h) (cmin) linear regression model.

T= Effective time per stump (cmin)			
T=T1+T2+T3+T4			
	Coefficient	Pr > t	R^2
T1= Passage			
Constant	47.376		
T2= Cleaning			
Constant	18.049		
T3= Cutting			
T3 = -11,148+ (a)*N			0.725
a	27.672	< 0.0001	
T4= Accessory			
Constant	34.001		
N= Number of stems per stump			

So the model could be used to felling time calculation in similar coppices with a different number of small stems per stump (Fig. 6).

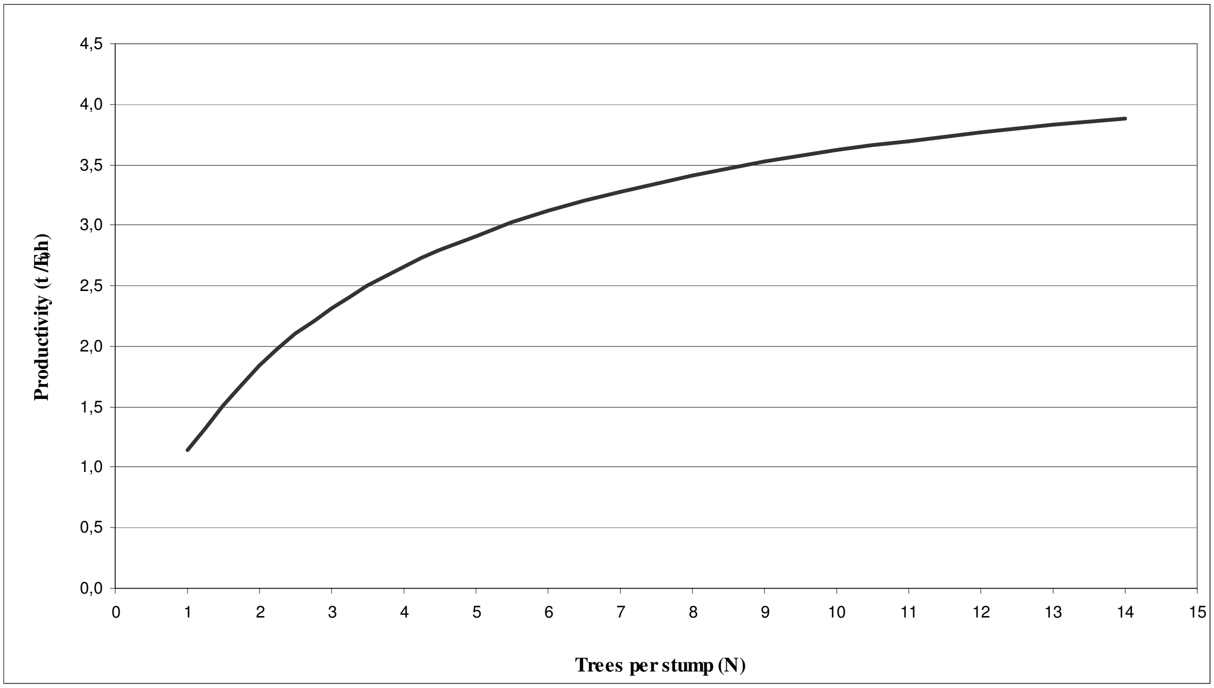

Figure 6: Effective productivity (two operators crew) in function of stems per stump, obtained by the time regression model and average sprout mass.

Extraction by farm tractor and forest winch

From time recorded on a total of 32 cycles were calculated effective times and main work parameters (Table 4), the results showed an high incidence of load connections times, even if this operation was carried out by two operators. The high proportion of accessory times were due to frequent load adjustment, to prevent trees losses and avoid obstacles (stumps and boulders).

The wide percentage of delays in $E_{15}h$, above 20%, was mainly related to trees collisions during cable pulling operation.

Table 4. Winching effective time elements (cmin), effective time percentages (E_0h), yard average features (variation interval) and effective productivity.

Cable extension (cmin)	120.3	20%
Load connection (cmin)	181.1	29%
Winching (cmin)	84.1	14%
Load unfastening (cmin)	82.7	13%

Accessory (cmin)	147.0	24%
Effective time (E_0h) (cmin)	615.1	
Delays (% $E_{15}h$)	26%	
Operators (n)	3	
Distance (m)	26 (8-50)	
Load (N. trees)	9 (3-16)	
Load (t)	0.20 (0.07-0.35)	
Effective productivity (t/E_0h)	1.9	
Effective productivity (o.d. t/E_0h)	1.5	

Extraction distance was found to be the only variable significantly related to effective time (Table 5), while tree number and corresponding load size had no effect on time elements, that was mainly explained by the fact that the average load resulted extremely low, if compared to winch pulling force.

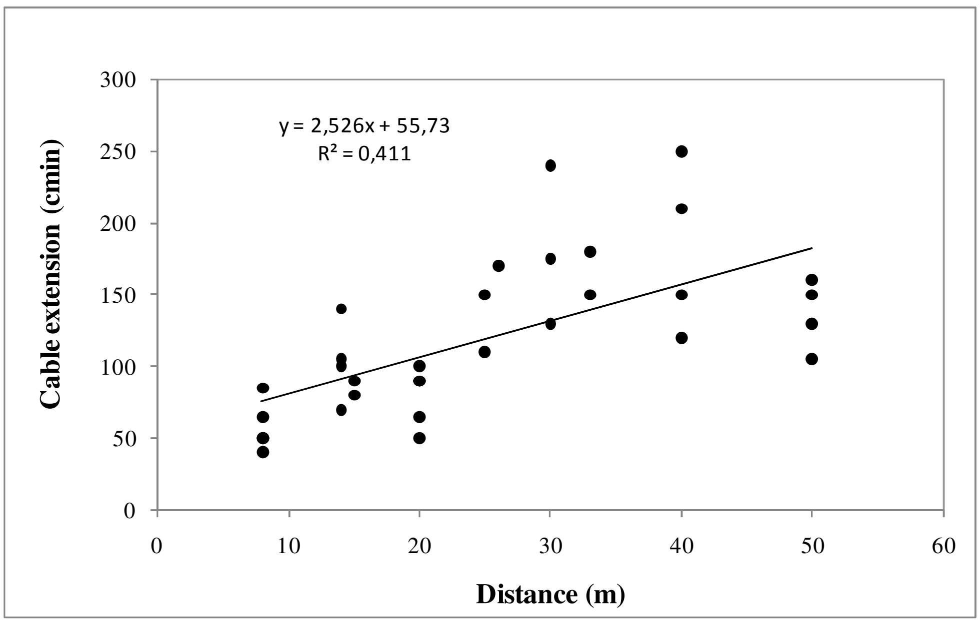

Figure 7: Cable extension time (cmin) as function of winching distance (m).

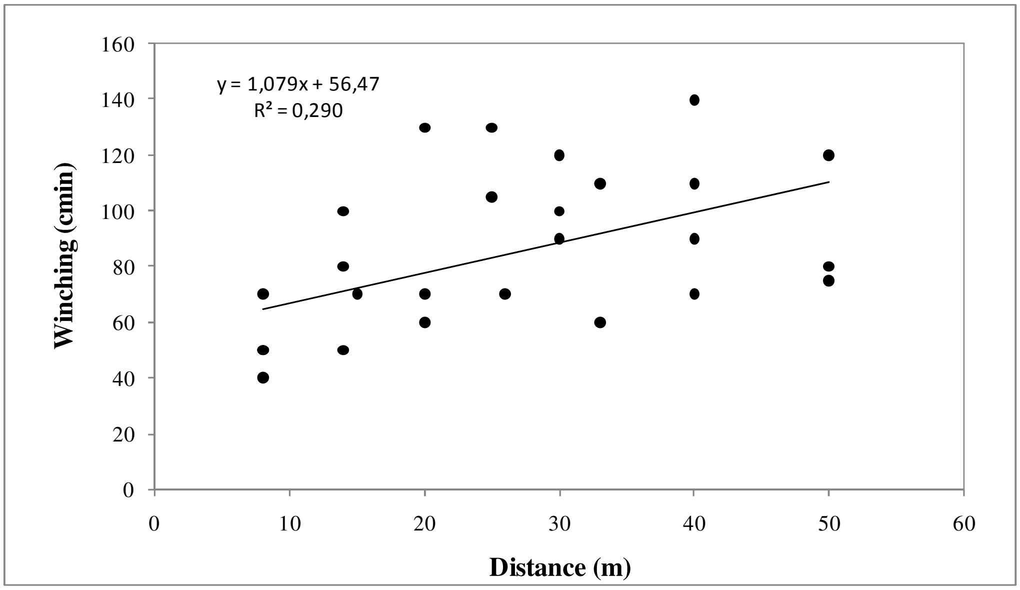

Figure 8: Winching time (cmin) as function of winching distance (m).

Table 5. Effective time per cycle (E_0h) (cmin) linear regression model in winching by farm tractor and forest winch.

T= Effective time (cmin)			
T=T1+T2+T3+T4+T5			
T1=Cable extension	Coefficient	Pr > t	R^2
T1= 55.730 + (a)*dist			0.411
a	2.526	< 0.0001	
T2=Load connection			
Constant	181		
T3=Winching			
T3 = 56.472+ (b)*dist			0.290
b	1.079	0.001	
T4=Load unfastening			
Constant	83		
T5= Accessory			
Constant	147		
dist= distance (m)			

Extraction by small cable yarder

Analysis of small cable yarder work times on a total of 35 cycles, allowed the calculation of average cycle times and the average work parameters (Table 6). Time analysis underlined an high incidence of times connected to load coupling, even if that operation was carried out by two operators, moreover the high incidence of accessory times was due to loads adjustment, previous to pulling phase.

Table 6. Yarding effective time elements (cmin), effective time percentages (E_0h), yard average features (variation interval) and effective productivity.

Carriage out (cmin)	119.3	17%
Loading (cmin)	160.6	23%
Carriage return (cmin)	193.2	27%
Unloading (cmin)	74.8	11%
Accessory (cmin)	155.0	22%
Effective time (E_0h) (cmin)	702.9	
Delays (% $E_{15}h$)	23%	
Operators (n)	3	
Distance (m)	37 (25-51)	
Load (Trees N.)	8 (2-12)	
Load (t)	0.18 (0.04-0.26)	
Effective productivity (t/h)	1.5	
Effective productivity (o.d. t /h)	1.1	

The effective time regression linear model identified for cable yarder (Table 7) showed that operations were significantly influenced by the extraction distance, while the number of trees per load was not correlated with time elements, this result was in accord with winching operations in the same stand.

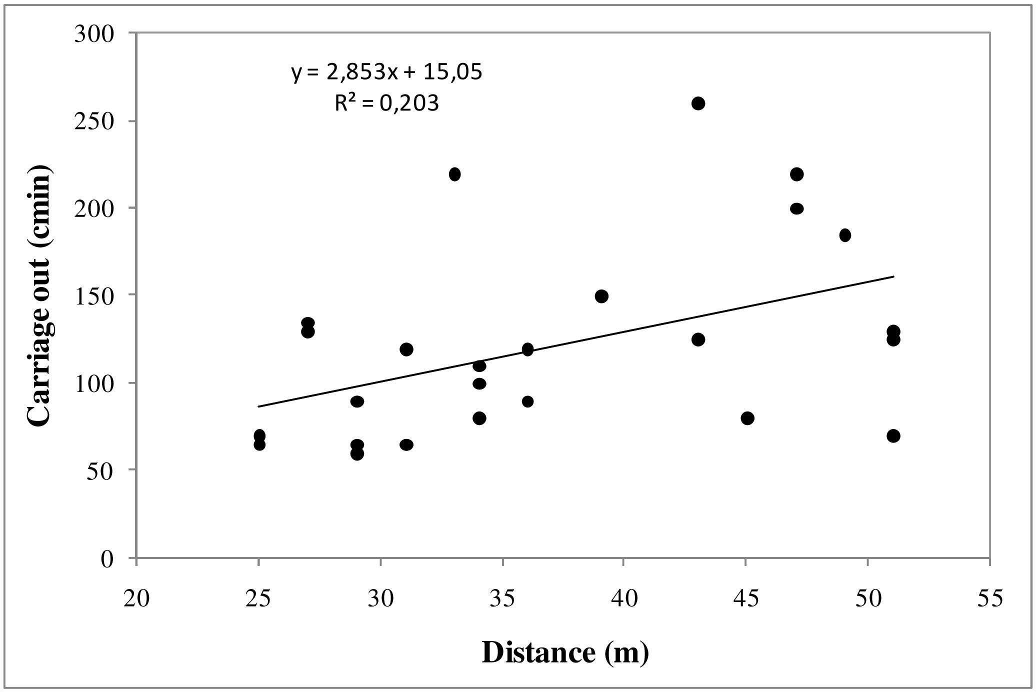

Figure 9: Carriage out time (cmin) as function of extraction distance (m).

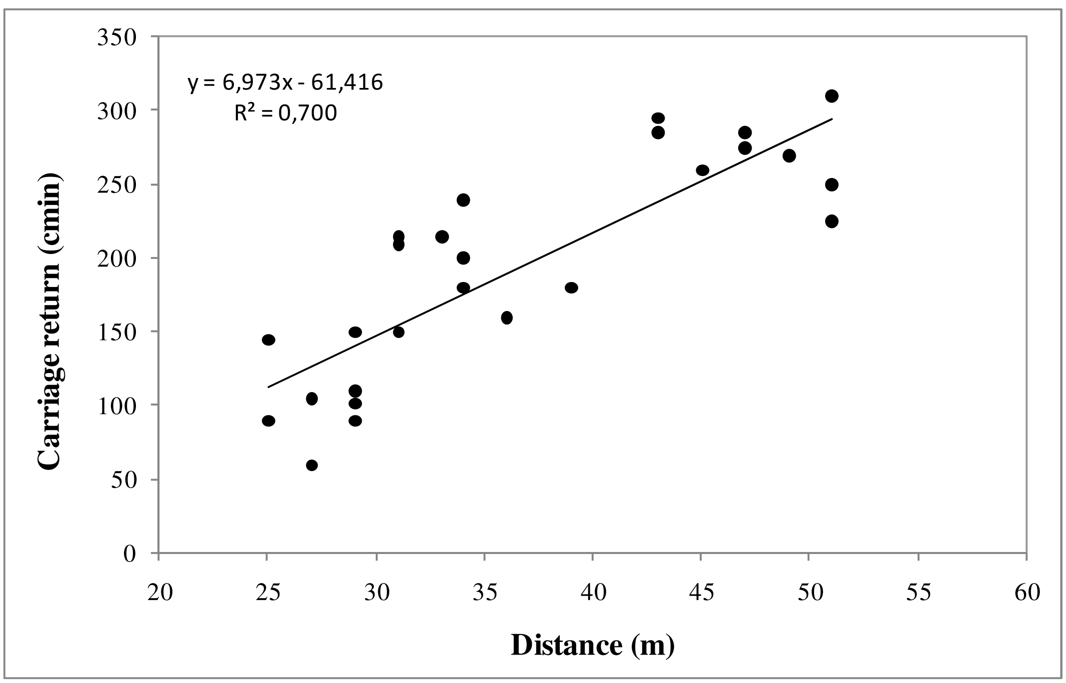

Figure 10: Carriage return time (cmin) as function of extraction distance (m).

Table 7. Effective time linear regression model (E_0h) (cmin) in extraction by small cable yarder

T= Effective time (cmin)			
T=T1+T2+T3+T4+T5			
T1=Carriage out	Coefficient	Pr > t	R^2
T1= 15.059 + (a)*dist			0.203
a	2.853	0.018	
T2=Loading			
Constant	161		
T3=Carriage return			
T3 = -61.416+ (b)*dist			0.700
b	6.973	<0.0001	
T4=Unloading			
Constant	83		
T5= Accessory			
Constant	155		
dist= distance (m)			

The comparison of the two extraction methodologies (winch and small cable yarder) underlined the difference in time models. In cable yarder model was noticed a lower correlation between distances and unload carriage movement, if compared to cable extension time in winching, the difference could be explained by the fact that winch rope was manually extended, so the time was easily influenced by man fatigue and ground obstacles, while the unload carriage movement was controlled only by gravity force. Moreover distances and extraction times showed an higher correlation in cable yarding, since loads were partially lifted from the ground, moving at constant speed, while during winching operations load pulling was affected by paths as well as distances, so reducing correlation intensity. In order to compare the two methods it is possible to use in time models the recorded average load, so calculating productivities for different extraction distances (Fig. 11).

In winching operations the incidence of delays resulted 3% higher than in cable yarding, moreover the percentage of tree collisions represented 15% of delays in winching, this percentage completely disappeared in cable yarding operations.

In addition to gross time ($E_{15}h$), in cable yarder extraction should be considered line installation and disassembling, this operation was carried out by a three operators crew and resulted in 8 working hours.

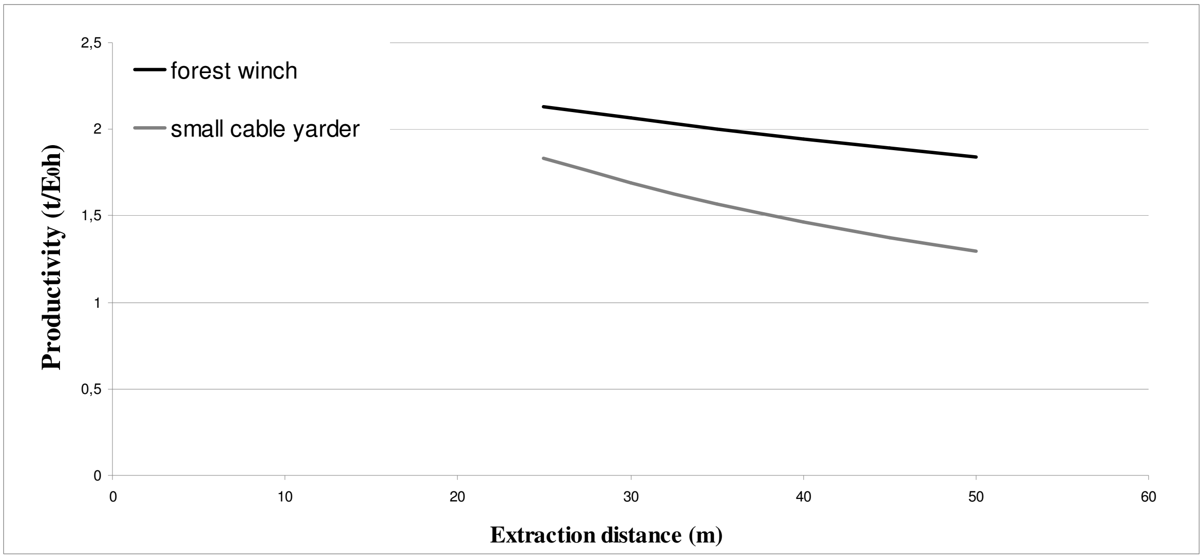

Figure 11: Effective productivity in whole tree extraction by forest winch and small cable yarder as function of extraction distance, using the average tree mass and a three operators crew.

Discussion

The small tree weight sampling allowed to accurately calculate the incidence of branches with a diameter below 3 cm, while in previous studies carried out in similar coppice stands this component was roughly esteemed in of 15-20% of whole trees fresh mass (Sperandio & Verani 1996; Nati & Spinelli 2009). In any case the results about moisture content are affected by fire passage, so the fresh mass information is not extendable in different stands, since commonly the fresh moisture content of fresh hardwood reaches 40-45%. In previous studies on whole tree harvesting, performed in 20 years old oak coppice stands (Verani et al. 2008), was identified an average stand mass of 50 t d.m., therefore the values found in our study are in this range. The assessment of biomass allocated in leaves was not carried out in our study. Accordingly in Italian coppice conditions we believe that leaves must return to the soil litter, being the tree component richest in nutrients, this could be possible with the traditional winter coppicing, when trees naturally lost their foliage.

According to Hippoliti & Piegai (2000), whole tree harvesting system reduces harvesting times by 50-70% when compared to traditional short wood method, since in short wood system trees are processed in the stand, while in whole tree system at roadside, so also ergonomic benefits can grow, especially if considering harvesting on steep terrain, like in our case.

The effective productivity found in felling and bunching operations were in line with Sperandio and Verani (1996) values, save for an higher incidence of delays, these are explained by the fire passage, causing an abnormal wear out of saw bars and forcing operators to frequent work interruptions, compared to normal cutting conditions.

In study results was identified an useful equation to calculate theoretical productivity of felling for different numbers of trees per stump, so the equation can be an useful tool in simulation of coppice harvesting performed with the whole tree system.

The small cable yarder achieved a effective productivity inferior to winch, if compared by the time model at the same extraction distance, with a difference ranging between 14% and 30%. In both extraction methods resulted an average load extremely inferior to machine potential payload, particularly for the cable yarder, reaching an average load 10% lower than forest winch. Assuming identical load for the two machines, the productivity gap resulted in the study could be reduced to a percentage between 5% and 22%.

The average load resulted from the cable yarder extraction was in line with the values found by Sperandio & Verani (1996) in their extensive surveys, where the average loads resulted of 0.1-0.3 t, using light cable yarders and whole tree harvesting system. In the same study the authors reported an average load of 0.6 t for the winching operation, equivalent to three times the value obtained in our study.

Comparing the cable yarder time model with previous models was found the same trend reported by Fabiano in (1994), since the time consumption in both models is strongly influenced by distances. However, in extraction yards considered by Fabiano (1994) the load per cycle reached 0.53 tonnes, so resulting in effective productivity 50% higher than in our case. However the machines used by Fabiano (1994) were light tower yarder, so with higher load capacity than the small cable yarder tested in our comparison. However, the cable yarder in our study had the possibility to reach a maximum payload of 0.8 tonnes (Marchi 1993).

The cable yarder extraction reduced delays connected to load collisions in comparison to forest winch and consequently total delays occurrence, this evidence was in accord with the literature results for small gravity cable yarder (Marchi 1993), since these machines allow to lift bunches butt ends and consequently to overpass obstacles like stumps or boulders.

Anyway the delay percentage recorded in cable yarder work was higher than values reported in other studies (Fabiano 1994), Fabiano thought a follow up study quantified delays in 15% of total time, while in our study delays resulted 23%, this could be mainly related to the scarce operators experience.

As in cable yarding stump collisions were reduced, a concomitant reduction of damages to small sprouts was attended. Contrary by the damage survey carried out by Giovannini and Marchi (2009), during the same research project, was recorded a significant statistical increase of damages in cable yarder area in comparison to winching. The damage increase could be explained by the repetition of load passages on the same trajectories, under the cable line, since stems and crowns were not totally hoisted, the result was a large damage extension, particularly near the cable yarder landing, where several passages occurred. While the winch cable followed different trajectories for each load, so reducing the damage occurrence. The same damage typology was recorded by Fabiano (1994), a year later extraction, recording the presence of weak sprouts at cable yarder landing.

As mentioned in the study results total operation cost must include cable yarder installation and disassembling times. As reported by Marchi (1993), time needed for installation and disassembling of a small gravity cable yarder line are shorter than for a traditional yarder line, however the limited amount of wood per line generated a large impact on gross time, this is a common effect when the cable yarder line is short and quantities of wood per line are too low. So short lines are difficult to manage, since the increase of installation time incidence and the small yard surface.

In Fabiano (1994) was suggested an installation time of 8.7 h per 100m of line, considering a crew of three operators and 2.9 h/100 m for disassembling, but the same author suggest the possibility to reduce times by experience, therefore installation could be reduced to 2-4 h per line and disassembling to 1-3 h.

From the economic assumptions and productivity results was possible to calculate the whole tree harvesting cost at the forest trail in €/t. The economic calculations considered two operators crew in felling operation and three operators in whole trees extraction.

For both extraction methods was considered the effective productivity reached at average distance of 30m. Gross productivity of felling was obtained by increasing 20% effective times recorded in the study, as resulted in delays analysis. For the cable yarder was assumed a 15% delays incidence as suggested by Fabiano, while in winching operation was considered an incidence of 20%, to include differences pointed out in the study. In addition to the delays occurrence in the cable yarder cost calculations were included the costs of line installation and disassembling, divided for the total biomass removal (12 t) in the line surface (2500 m^2). Therefore the cost of installation and disassembling resulted of 22 €/t. From these assumptions resulted whole tree costs reported in Table 8 and Table 9. From these results was evident that cable yarder compromised economic sustainability of extraction operations, since the high installation costs and low biomass removal.

Table 8: Operation cost resulted from the field study, in case of extraction by forest winch and farm tractor.

	Hourly machine cost [€ h^{-1}]	Hourly labour cost [€ h^{-1}]	Operation cost [€ h^{-1}]	Gross productivity [t h^{-1}]	Total cost [€ t^{-1}]	Percentage of total cost [%]
Felling	2,80	30,00 (2)	32,80	1,75	18,74	36%
Winching	14,58	44,00 (3)	58,58	1,75	33,47	64%
Total					**52,22**	

( ) Number of operators

Table 9: Operation cost resulted from the field study, in case of extraction by small cable yarder.

	Hourly machine cost [€ h^{-1}]	Hourly labour cost [€ h^{-1}]	Operation cost [€ h^{-1}]	Gross productivity [t h^{-1}]	Total cost [€ t^{-1}]	Percentage of total cost [%]
Felling	2,80	30,00 (2)	32,80	1,75	18,74	22%
Yarding	21,35	44,00 (3)	65,35	1,48	66,21	78%
Total					**84,95**	

( ) Number of operators

Under current market conditions firewood price at roadside (with diameter over 3 cm) resulted 70 €/t, subtracting a motor-manual processing cost of 25 €/t (Nati & Spinelli 2009) can be calculated a whole tree price of 45 €/t; price for wood chips in these stands resulted 40 €/t, so subtracting the chipping cost, whole tree price results 28 €/t; the economic balance underlines the convenience to integrate chips with firewood production, since as previously shown 69% of three biomass can be addressed to the production of firewood, reducing economic losses in coppice harvesting.

If we consider the clear cutting of a green coppice stand (traditional coppicing), it could be possible to increase study productivities by 15% to take into account the higher moisture content of fresh material and at the same the lower overheating of chainsaw bar in felling operations, with subsequent delays reductions. Assuming that line installation and disassembling time will be reduced to only 4 hours by operators experience, the subsequent cost for installation and disassembling will be reduced to 10 €/t, reaching total harvesting costs shown in Table 10 and 11.

Table 10. Operation cost of green coppice harvesting, in case of extraction by forest winch and farm tractor.

	Hourly machine cost [€ h^{-1}]	Hourly labour cost [€ h^{-1}]	Operation cost [€ h^{-1}]	Gross productivity [t h^{-1}]	Total cost [€ t^{-1}]
Felling	2,80	30,00 (2)	32,80	2,01	16,30
Winching	14,58	44,00 (3)	58,58	2,01	29,11
Total					**45,41**

( ) Number of operators

Table 11. Operation cost of green coppice harvesting, in case of extraction by small cable yarder.

	Hourly machine cost [€ h^{-1}]	Hourly labour cost [€ h^{-1}]	Operation cost [€ h^{-1}]	Gross productivity [t h^{-1}]	Total cost [€ t^{-1}]
Felling	2,80	30,00 (2)	32,80	2,01	16,30
Yarding	21,35	44,00 (3)	65,35	1,70	48,44
Total					**64,74**

( ) Number of operators

The cost analysis pointed out that only in the case of winching, increasing productivity, it could be possible to reach economic sustainability (Table 10), selling harvested biomass as firewood. While harvesting operations could not reach the sustainability if the whole mass is addressed to energy chips. So in these stands it is advisable to perform an integrated harvesting of the two products with the whole tree harvesting system.

Based on machine masses, fuel consumption recorded in the study and calculated lubricant consumption was carried out an inventory of CO_2 emissions during harvesting operations as in Table 12 and 13.

Table 12. Kg Co2 eq. /MWh emissions resulted in the field study, in case of extraction by forest winch and farm tractor.

		Direct emission	Indirect emission		Total emission	
			Fuel production	Machine production		
Chainsaw	Mixture	0,42	0,02	0,002	0,45	13%
	Lubricant		0,02			
Farm tractor and forest winch	Diesel	2,45	0,10	0,467	3,04	87%
	Lubricant		0,02			
%		82%	18%		3,49	

Table 13. Kg Co2 eq. /MWh emissions resulted in the field study, in case of extraction by small cable yarder.

		Direct emission	Indirect emission		Total emission	
			Fuel production	Machine production		
Chainsaw	Mixture	0,42	0,02	0,002	0,45	10%
	Lubricant		0,02			
Small cable yarder	Diesel	3,20	0,13	0,666	4,03	90%
	Lubricant		0,03			
%		81%	19%		4,48	

STUDY III

Materials and Methods

The study was carried out in a first thinning of a pine forest, located in the municipality of Fratta Todina (PG) (42 ° 52'N, 12 ° 20'E) in Umbria. The stand was an Aleppo pine (*Pinus halepensis* Miller) plantation, 35 years old, subjected to a first selective thinning. The terrain was in second class of slope (20-40%), with low roughness. The area presented a good accessibility since a forest trail was situated at the bottom and a forest road at the top. The pine stand was planted with a regular tree spacing of 2.5x2.5m, so at thinning time presented a density of around 1600 trees/ha. This first thinning was scheduled with a selective pattern, using a low harvesting intensity, removing dominated, fork and dead trees, so reducing density to 1263 trees ha^{-1} with an incidence of 21 % (on tree number).

Primarily on a sample area of 400 m^2 all tree diameters were measured at breast height (dbh) for a thinning treatment simulation. Through diameter distribution analysis, 20 sample trees were selected from classes with the highest frequency (dbh 10-15-20 cm). Subsequently sample trees were felled, every stem was divided into 2m logs, so tree portion were weighed on a certified scale. Branches were separately weighed on the same scale. Crown samples were carried to a laboratory in order to measure the weight incidence of branches, cones and needles. For each sample tree, were collected small discs from base, middle height and tree top. Sample discs were fresh weighed, then dried in a laboratory stove at 103°C (UNI 9091/2) in order to measure fresh material moisture content.

The full tree harvesting was carried out by a private contractor. Trees were motor-manually felled, so winched and skidded to the landing by a farm tractor with forest winch. Then whole trees were chipped using a self propelled drum chipper (320 kW), so chips were transported to a power plant in Terni (distance of 75 km) by a truck and trailer (payload of 50 m^3).

In the stand area were identified two homogeneous sub-areas of 0.3 ha. In the two sub-areas were compared two different felling methods, using the traditional chainsaw in the first area and the same chainsaw equipped with a prototype of felling frame in the other (Fig. 1).

The prototype of universal felling frame, weighing only 1 kg, can be attached to every model of professional chainsaw, letting the machine cut parallel to ground surface, even on sloping ground, where the traditional frame, currently used in the Nordic Countries, could not be used correctly. In both sub-areas motor-manual felling was performed by the same chainsaw (STIHL 023 2.3 kW), letting trees falling between stand rows, with tree butt ends pointed to a forest trail, creating preferential winching lines.

Since the operator was not experienced in work with the felling frame, half day of practice was carried out on an adjacent stand area.

A work time analysis was carried out in felling operations. In effective time (E_0h) recording were included the following time elements (same time elements were used in the two sub-areas):

Passage: time between the complete tree felling and the subsequent tree cutting.

Cutting: time between the beginning of cutting process to complete tree severance from the stump.

Directed tree falling: time between complete severance from the stump and complete tree falling.

Accessory: other necessary times (eg. stump cleaning, tree bunching, stump trimming).

A total of 88 times cycles were recorded for tradition chainsaw and 112 for chainsaw with felling frame.

In addition to effective times analysis (E_0h) were recorded short delays in $E_{15}h$. Delays were used to quantify the conversion of effective productivity in total productivity ($E_{15}h$).

The recorded effective time was divided into hourly sessions, in order to compare the hourly effective productivity, given by the ratio between the quantity of product (N. trees, t, o.d.t) and effective work time (E_0h).

Effective times and effective productivities resulted from the two methods were compared by ANOVA statistical analysis ($p < 0.05$).

During tree felling were recorded diameters at stumps, in order to compare average sub-areas diameters using T-test ($p < 0.05$), and to analyse possible correlations with felling times.

Figure 1: Comparison of directed tree felling by chainsaw (on the left) and by chainsaw with felling frame (on the right), the operator uses tongs to direct tree falling.

On total felling surface the winching and skidding was carried out by a tracked farm tractor (SAME Explorer 60 kW) and a forest winch (TERMACCH 5000, pulling force 50 kN) with 11 mm cable diameter and 80m length (Figure 2). These operations were performed by a three operators crew.

During the winching and complementary skidding operations was carried out a detailed continuous time recording, analyzing effective work time (E_0h) and total time including short delays ($E_{15}h$).

The effective work time was divided into the following work elements:

Travel empty: time needed by farm tractor to reach winching lines from the landing area.

Cable extension: time between the cable release from the winch drum and its elongation to the further bunch of trees to be winched.

Load connection: time between the complete extension of the cable to the complete coupling of bunches to the winch cable.

Winching: time between the start of cable pulling to extraction of trees to the winch blade.

Skidding: time needed by farm tractor to skid trees from winching lines to the landing

Load unfastening: time between the cable release to complete load unfastening.

Stockage: time needed by farm tractor to pile trees with the frontal blade

Accessory: other necessary times (eg. tractor manoeuvring, load adjustment).

Effective time was recorded by a tree chronometer table, for each work cycle were measured:

- Trees number
- Winching distance
- Skidding distance.

Analysis of effective time allowed to find significant correlations between work time and measured variables and to calculate linear regressions of the variables that significantly ($p < 0.05$) affected each work element, creating an additive model for effective time calculation.

Figure 2: Winching of tree bunches and skidding by farm tractor with forest winch.

To assess thinning operation also from silvicultural point of view, at the end of skidding operation, in each sub-area, was carried out a survey of damages. In this survey was counted the number of trees with an evident damage on wood fibres. So the damages in the two sub-areas were compared using X^2 analysis ($p<0.05$).

Based on gross productivity, resulted from the time study, integrated by literature gross productivity coefficients and using Hippoliti (1997) formula were calculated hourly machines costs. In cost calculations was considered a value of 700 € for the chainsaw with felling frame and 38.000 € for the tracked farm tractor with forest winch. Assuming a lifespan of 2.000 hours for the chainsaw and 10.000 hours for the farm tractor (Hippoliti 1997). Machine costs were added to labour cost, derived from national contracts. So were calculated the whole tree felling and extraction (to roadside) costs.

Results

The analysis of pine stand characteristics and the average tree features (Tab. 1), pointed out that 29% of fresh biomass can be obtained from tree crown (including branches, cones and needles, which respectively represented 20.9%, 6.5% and 1.6% of whole tree fresh biomass). Tree moisture content at harvesting time exceeded 50%, so material seasoning was suggested, in order to maximize subsequent energy conversions.

Table 1. Stand and average tree characteristics.

Density (Trees ha^{-1})	1600
Dbh (cm)	17.6
Basimetrical area (m^2/ha)	39
Height (m)	13.2
Stem volume (dm^3)	147
Total stem volume (m^3 ha^{-1})	235.7
Stem mass (kg)	146.8
Whole tree mass (kg)	212.1
Moisture content (%)	52
Whole tree dry mass (o.d. kg)	101.8
Total Mass (o.d. t ha^{-1})	162.9
Thinning removal	
Removal (N. Trees ha^{-1})	337
Dbh (cm)	12.8
Stem volume (dm^3)	85
Stem mass (kg)	84.3
Whole tree mass (kg)	118.6
Removal mass (t ha^{-1})	39.9
Removal dry mass (o.d. t ha^{-1})	19.1

From weight sampling were obtained two regressions, showing stem and whole tree dry biomass in function of tree diameter (dbh) (Fig. 3). These regressions can be useful to calculate harvestable whole tree biomass (for diameters between 10 and 20 cm) in similar stand conditions.

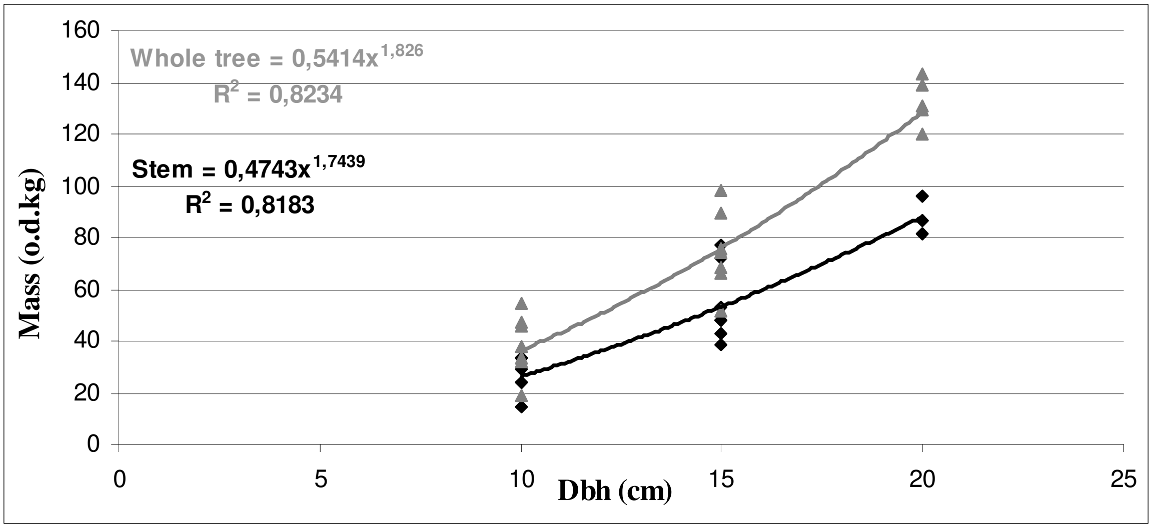

Figura 3: Whole tree and stem dry mass as function of breast height diameter (dbh).

In the two sub-areas were recorded not significant differences in tree diameter at stump ($p = 0.118$), with an average of 16.5 cm in the first area and 15.1 cm in the other.

Analysis of work time (Table 2) pointed out a significant reduction of effective time using the felling frame, in particular this tool reduced the time needed to pass from a tree to the subsequent, this difference can be explained by a reduced operator fatigue since he could work in a straight upright position, so he reduced movement effort. Besides the felling frame allowed a time reduction in tree falling, since the operator used a free hand to carry out this task, even during the cutting process. The advantages obtainable by the frame, in this case, resulted in a significant higher productivity when compared to traditional chainsaw.

Table 2. Effective time elements in felling operation (cmin) and effective productivity results, single operator crew, standard deviation between parenthesis, different letters in each row show statistical significant difference ($p<0.05$).

	Effective time		Effective time percentage	
	Chainsaw cmin (s.d.)	Felling frame cmin (s.d.)	Chainsaw	Felling frame
Passage	83.3 (15.7) a	57.5 (13.5) b	35.9%	32.0%
Cutting	37.9 (8.7) a	32.4 (5.6) a	16.3%	18.0%
Directed falling	50.8 (28.0) a	34.9 (13.8) a	21.9%	19.4%
Accessory	60.2 (42.4) a	55.2 (25.0) a	25.9%	30.7%

Effective time (E_0h)	232.1 (34.4) a	180.0 (36.7) b
Effective Productivity (Trees/E_0h)	26 a	35 b
Effective Productivity (t/E_0h)	3.1 a	4.1 b
Effective Productivity (o.d. t/E_0h)	1.5 a	2.0 b

The effective time analysis showed a significant correlation between the diameter at stump of felled trees and cutting times, the data recorded allowed to identify linear regressions models to relate diameter at stumps and cutting time for the two felling methodologies (Table 3).

From the prediction model resulted that felling frame cutting time per diameters of 10 cm are 23% lower than traditional chainsaw, the difference between the cutting time is reduced to 2% per diameters of 15 cm, while per diameters of 20 cm the frame cutting time become 10% superior to traditional chainsaw.

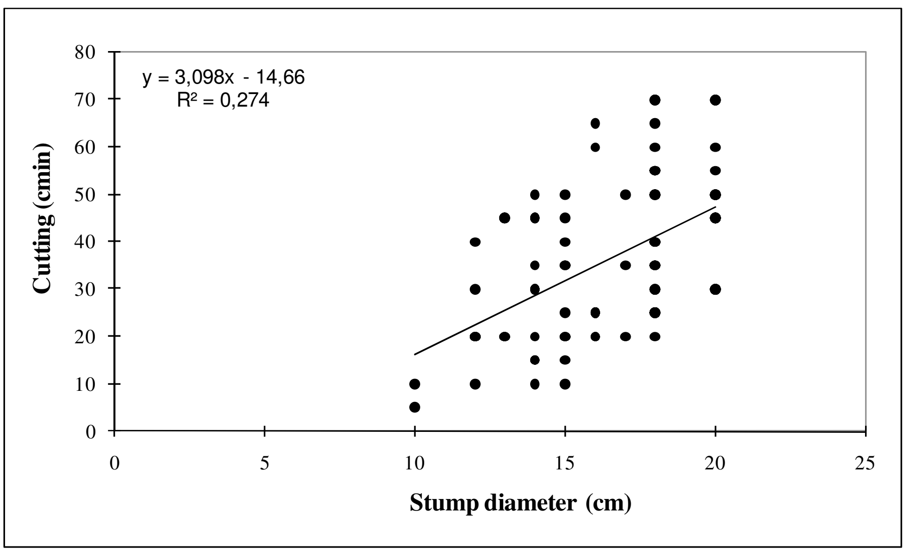

Figure 4: Cutting time (cmin) as function of stump diameter (cm) (Chainsaw).

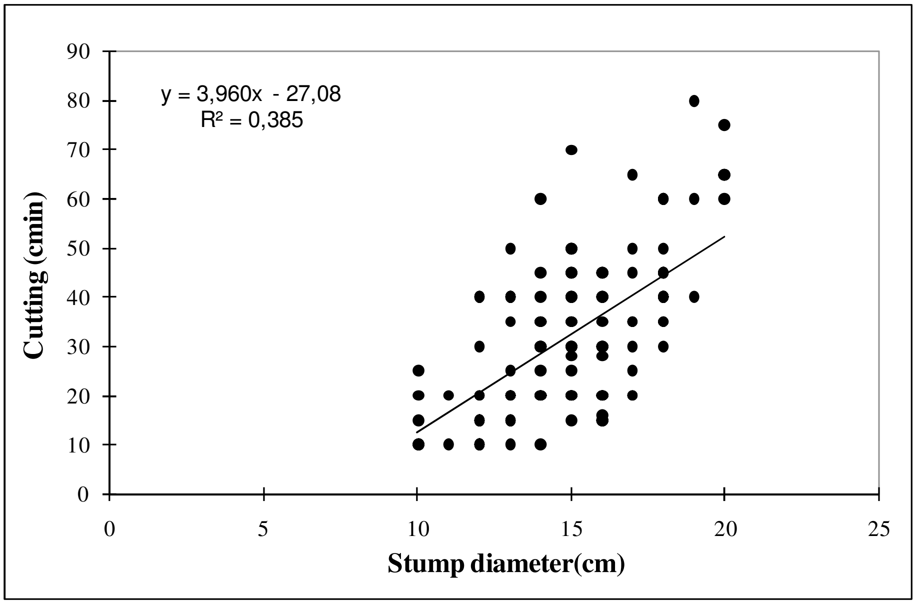

Figure 5: Cutting time (cmin) as function of stump diameter (cm) (Felling frame).

Table 3. Effective time (E_0h) (cmin) linear regression model in directed felling operation.

T=Effective time (cmin)	Chainsaw			Felling frame		
T=T1+T2+T3+T4						
	Coefficient	Pr > t	R²	Coefficient	Pr > t	R²
T1=Passage						
Constant	83.274			57.515		
T2=Cutting						
T2 = a + (b)*d			0.274			0.385
a = Constant	-14.668			-27.083		
b	3.098	< 0.0001		3.960	< 0.0001	
T3=Directed falling						
Constant	50.774			34.888		
T3=Accessory						
Constant	60.238			55.169		
d= stump diameter (cm)						

Delays analysis showed an impact on gross time ($E_{15}h$) of 35% with traditional chainsaw, and 26% with the chainsaw equipped with felling frame, the delays reduction was mainly due to shorter operator pauses using the felling frame.

The measurements of winching and skidding operations on a total 62 cycles allowed to calculate working times, the main work parameters, and effective productivities (Table 4).

Table 4. Winching and skidding effective time elements (cmin), effective time percentages (E0H), average study features (variation interval) and effective productivity (three operators crew).

Empty travel (cmin)	222.7	18%
Cable extension (cmin)	73.0	6%
Load connection (cmin)	193.3	16%
Winching (cmin)	80.5	6%
Skidding (cmin)	286.2	23%
Load unfastening (cmin)	139.0	11%
Stockage (cmin)	114.7	9%
Accessory (cmin)	133.0	11%
Effective time (E_0h) (cmin)	1242.4	
Delays (% E_{15}h)	7%	
Operators (n)	3	
Winching distance (m)	23 (5-50)	
Skidding distance (m)	127 (20-320)	
Load (Trees N)	5 (2-12)	
Load (t)	0.6 (0.2-1.4)	
Effective productivity (t/E_0h)	2.9	
Effective productivity (o.d. t/E_0h)	1.4	

The correlation analysis showed that winching and skidding distances were the variables significantly affecting the effective work time. In addition the number of trees in each load affected effective times, this variable influenced particularly load connection and skidding times, as noticed in the linear regression model, but the effect was smaller than for distances (Table 5).

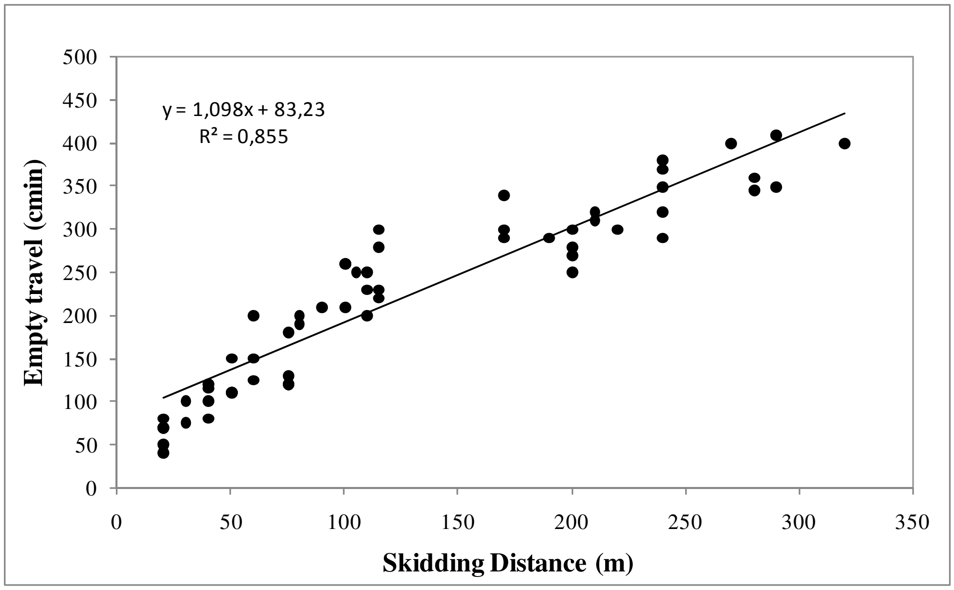

Figure 6: Empty travel time (cmin) as function of skidding distance (cm).

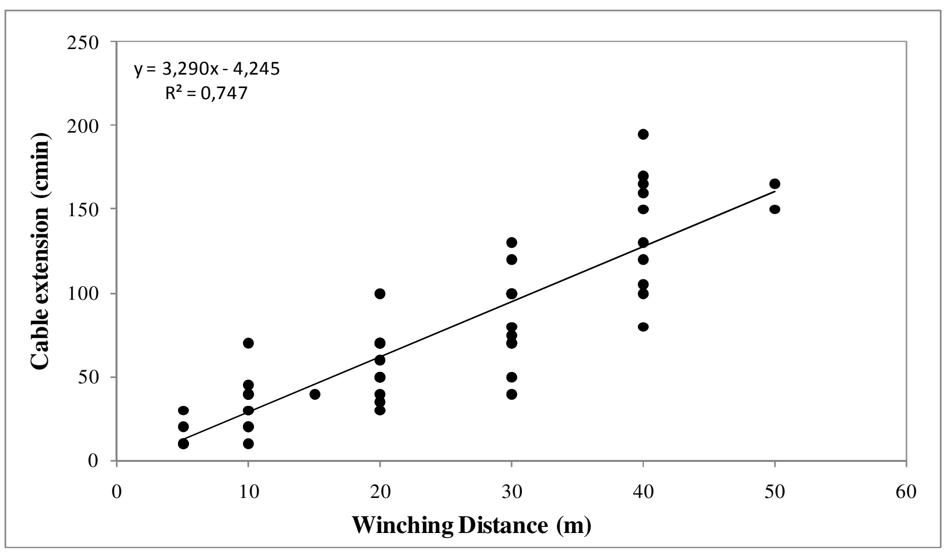

Figure 7: Cable extension time (cmin) as function of winching distance (cm).

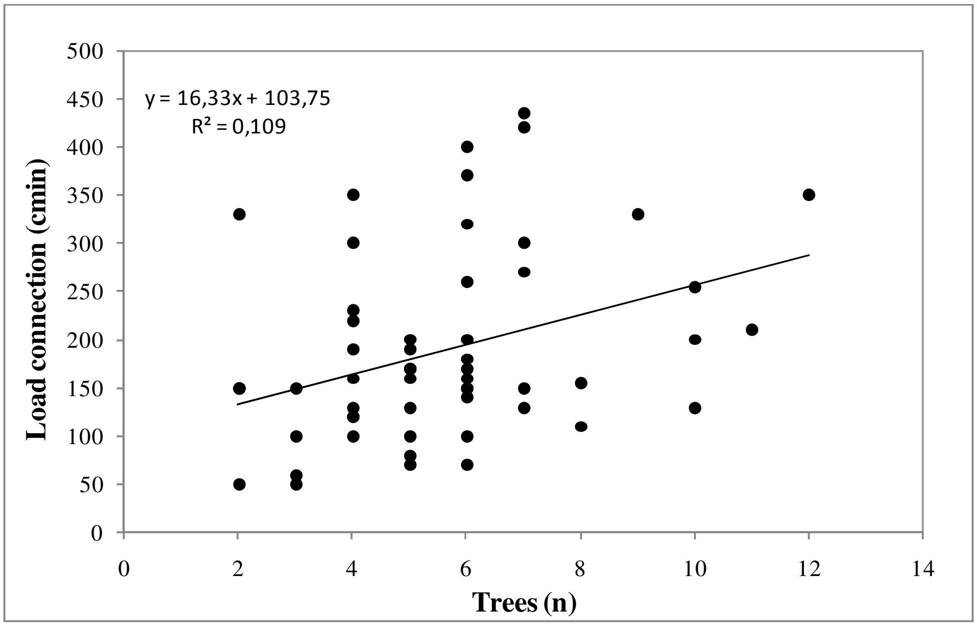

Figure 8: Load connection time (cmin) as trees number (n).

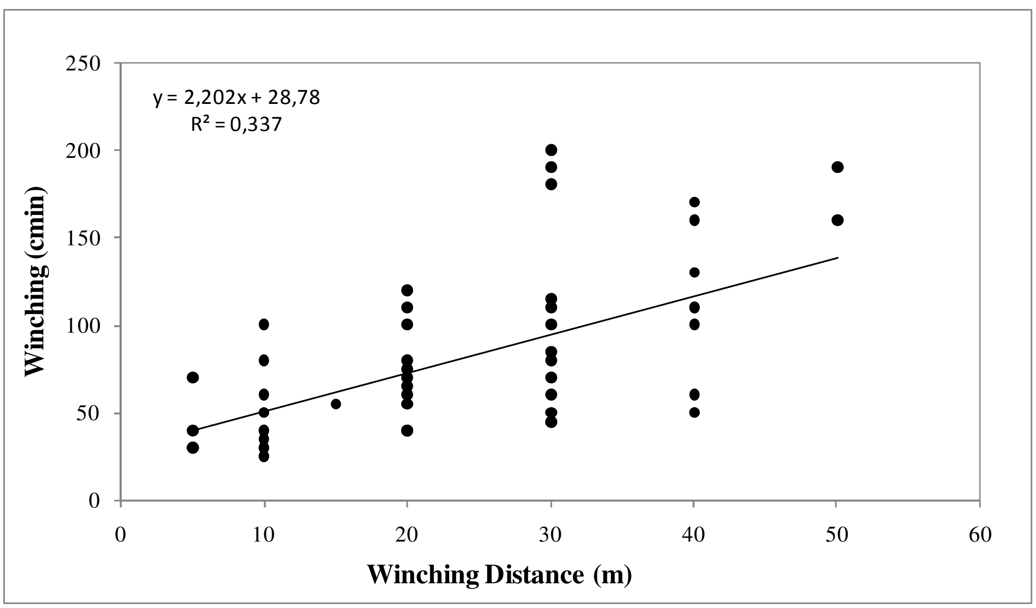

Figure 9: Winching time (cmin) as function of winching distance (m).

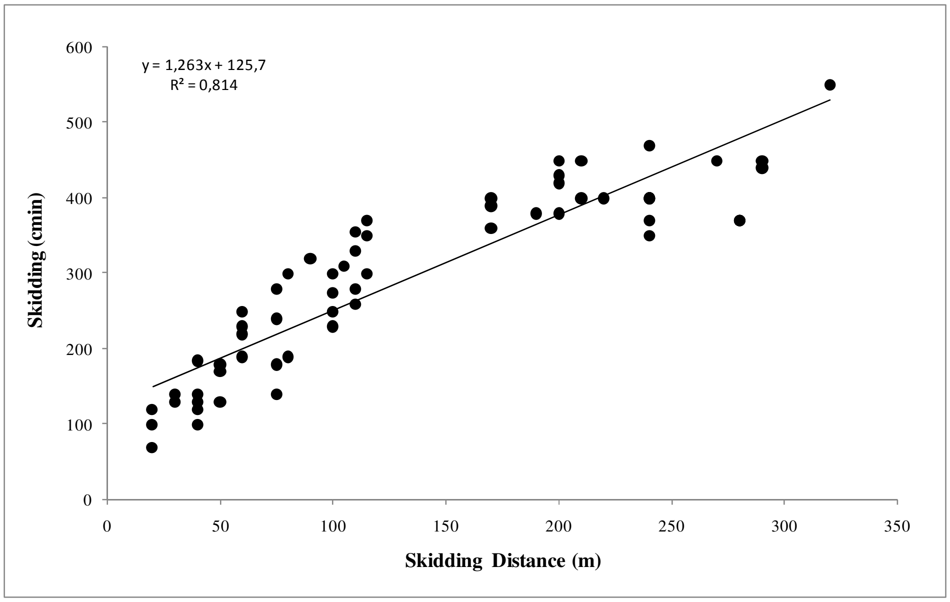

Figure 10: Skidding time (cmin) as function of skidding distance (m).

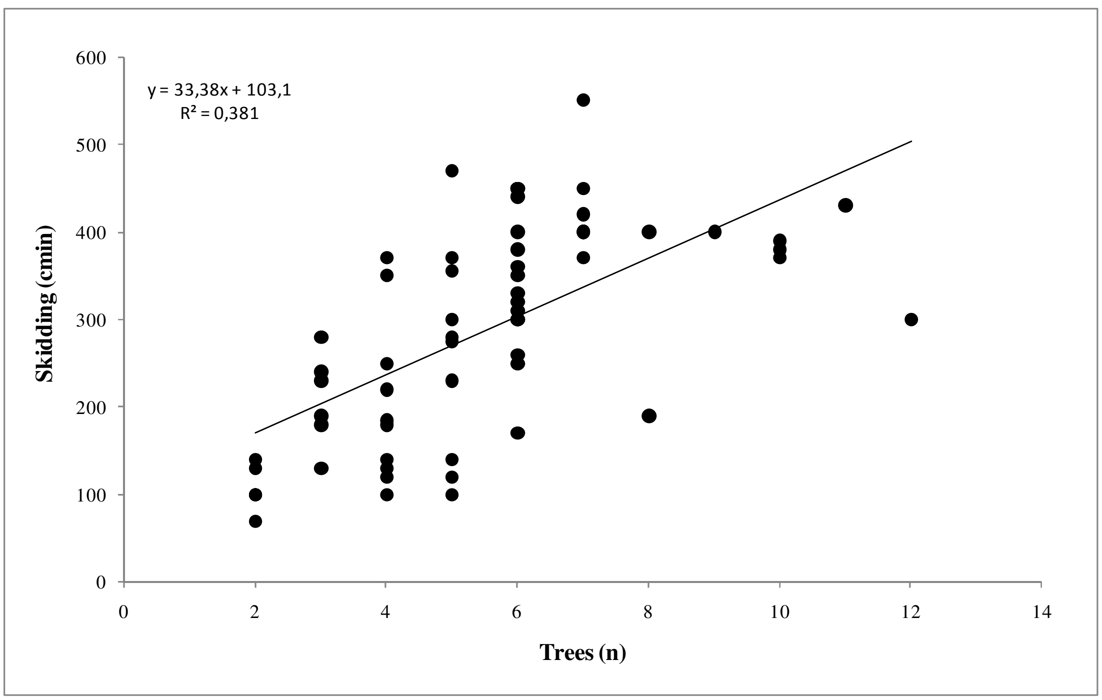

Figure 11: Skidding time (cmin) as function of trees number (n).

Table 5. Effective time per cycle (E_0h) (cmin) linear regression model in winching and skidding by farm tractor and forest winch (three operators crew).

T= Effective time (cmin)			
T=T1+T2+T3+T4+T5+T6+T7+T8			
T1=Empty travel	Coefficient	Pr > t	R^2
T1= 83.238 + (a) dist1			0.855
A	1.098	< 0.0001	
T2= Cable extension			
T2= - 4.246 + (b)*dist2			0.747
B	3.290	< 0.0001	
T3= Load connection			
T3= 103.750+(c)*N			0.109
C	16.330	0.009	
T4= Winching			
T4 = 28.788+ (d)*dist2			0.337
D	2.203	< 0.0001	
T5= Skidding			
T5= 87.571+ (e)*dist1+(f)*N			0.840
E	1.122	<0.0001	
F	10.238	0.003	
T6=Load unfastening			
Constant	139		
T7= Stocking			
Constant	115		
T8= Accessory			
Constant	133		
Dist1= Skidding distance (m)			
Dist2= Winching distance (m)			
N = Trees number			

Using in time model the average number of trees recorded in the field study (5) and the average winching distance (23 m), using the average load (0.6 t), it is possible to obtain a model of productivity for different skidding distances (Fig. 12).

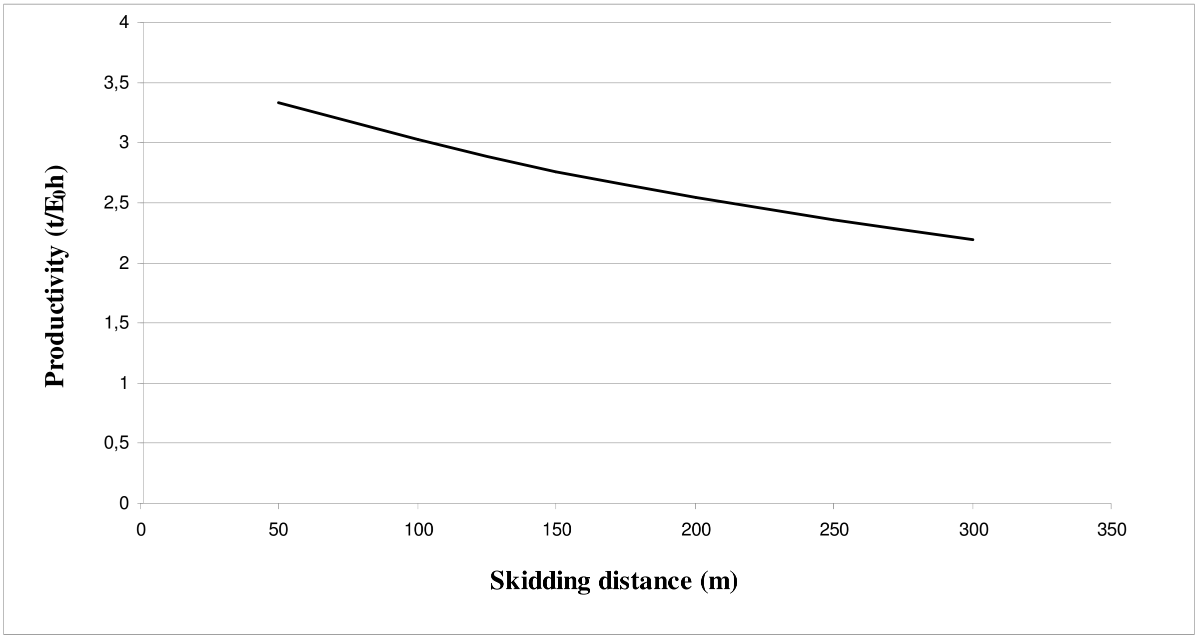

Figure 12: Effective productivity in whole tree winching and skidding by forest winch as function of skidding distance, using the average tree mass in the study and a three operators crew (winching distance 23 m).

The damage frequency found on residual stand trees, after felling, winching and skidding operation, was higher in the subarea felled with traditional chainsaw, where 21% of trees were damaged on fibers, while the percentage was significantly reduced to 8% in the sub area felled with chainsaw and felling frame ($X^2_1 = 6.386$, p= 0.012). The result underlined the improvement achieved with the felling frame on directional tree falling, so reducing possible damages in winching operations.

Discussion

The wood analysis pointed out that the fresh material was characterized by a moisture content superior to 50%, but in line with 45%-50% found harvesting Mediterranean pine forests, as resulted in Magagnotti et al. (2009). The field study results suggested biomass seasoning to reduce moisture content at landing, before transportation to energy conversions plants, especially if the residual material will be used in small boilers, requiring wood moisture content inferior to 35% (Hakkila 1989).

The model for biomass calculation, found in the study, allow to know biomass content in trees included in different diameter classes, so it is possible to integrate dendrometric tables, actually used for mass calculations, derived from National Forest Inventory, which generally not included fine biomass components. So using the equation found in the study it will be possible to calculate the harvestable biomass removal in different stand conditions. Besides the assessment of crown components could address future choices between the integral use of tree crown and possible release of tree portions. Indeed, from the biomass analysis resulted that needles represent only 1.6% of the whole tree biomass, so releasing this component on the ground would not cause significant losses from economic point of view, but the practice could ensure ecological sustainability of thinning when whole trees are harvested. However appropriate technologies to allow small particles release must be identified. In Mediterranean conditions a possible solution could be felled trees seasoning in the forest, in order to allow easy separation of needles during whole tree extraction, but this process could generate a bait for pests and fire.

The dry biomass removal recorded in thinning operation positioned this stand among pine forests with a scarce growth, where biomass removal in thinning reaches 25-30 o.d. t /ha, in these cases it is advisable the use of whole trees as energy chips, applying the whole tree harvesting system (Magagnotti et al. 2009).

The field comparison of the two felling methodologies showed that chainsaw with felling frame significantly reduced the felling time per tree and therefore increased effective productivity by 30%, even in slope terrain harvesting conditions.

Two models predicting cutting times for different stump diameters were derived from working time analysis, only cutting time element resulted affected by to stump diameters, so a limited amount of variability in felling operations was explained. The felling time calculation models showed that an increase of stump diameters from 10 to 20 cm cause the loss of the frame competitiveness, since cutting difficulties on trees over 15 cm. Indeed Hakkila (1989) reported the possibility to increase the felling productivity by 20-30%, when comparing felling frame to the traditional chainsaw, but on condition that stem diameters remained under 12 cm. In our study traditional chainsaw productivity resulted 30%-40% inferior to values reported in other thinning operations (Magagnotti et al. 2009). The productivity gap could be attributed to the high incidence of directional falling times, since the difficulty to direct trees falling in a thinning operation. The incidence tree felling delays was positioned in the average range for motor-manual operations (Spinelli et al. 2003), since generally representing 20% of gross working time. The felling frame allowed a 9% reduction in short delays occurrence, since the possibility to reduce operator fatigue, as suggested by Hakkila (1989), improving ergonomics. During the study were not recorded particular drawbacks related to the use of a modified felling frame on slope terrain, moreover the modifications made on the traditional felling frame enhanced cutting performance, since the frame allowed cuttings parallel to the ground surface, so reducing time in stump trimming, when compared to a traditional chainsaw operation.

The model obtained for winching and skidding operations showed a strong dependence between distances and work times (Figure 13), as evidenced in thinning operations in Alpine spruce stands, where whole trees were harvested (Spinelli et al. 2003). Comparing the found model to Spinelli et al (2003) the maximum deviation of effective productivity resulted inferior to 10%. However the crew carrying out the operation consisted of three operators in our study while two operators in Spinelli et al. (2003).

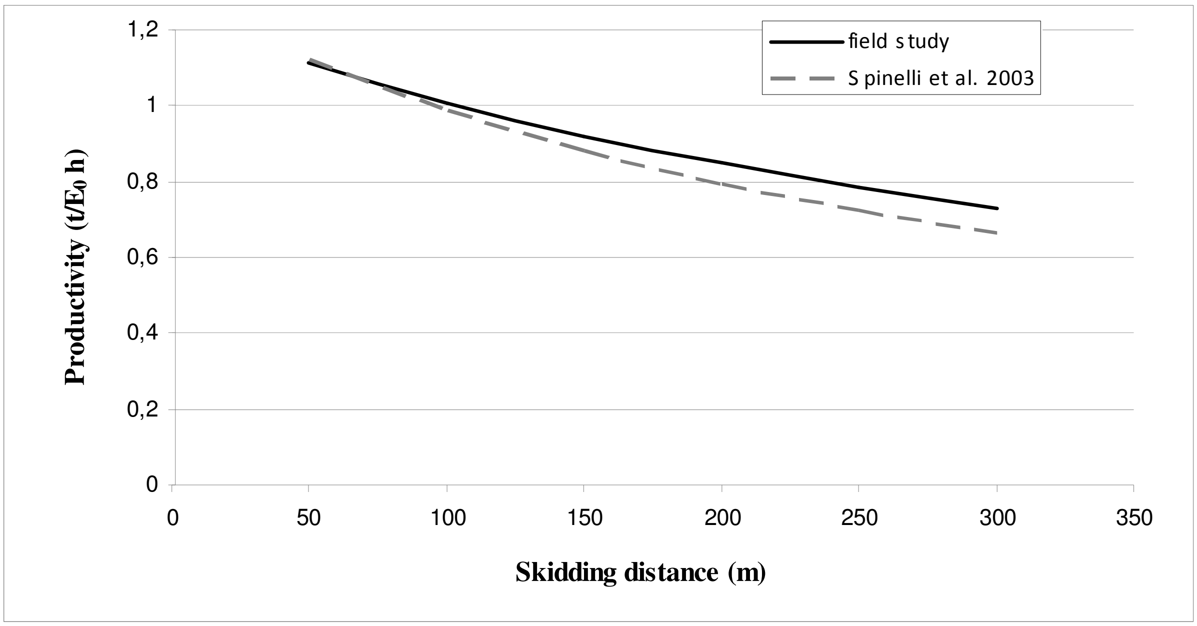

Figure 13. Comparison of effective productivity per operator from the field study and Spinelli et al. (2003) model as function of skidding distance (load 0.6 t and winching distance 23 m).

The productivity model obtained in the study allows to identify factors needed to maximize work productivity. So assuming a single tree increase in the average load, consequently effective time will increase 1%, while effective productivity 19% (Fig. 14).

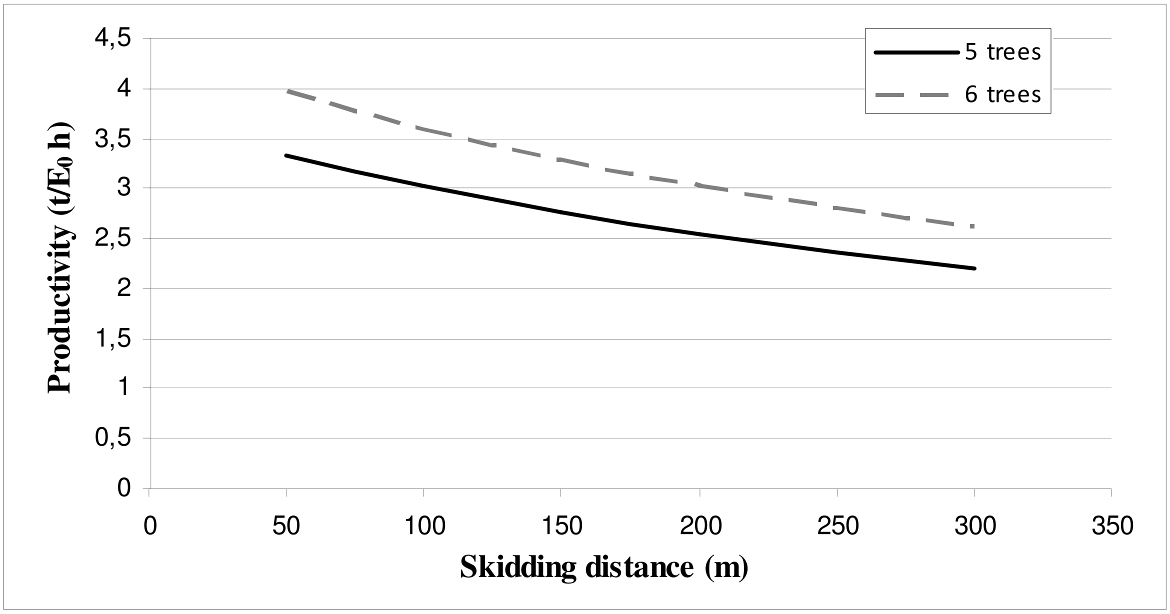

Figure 14. Effective productivity variation in case of load increase (three operators crew).

The delays occurrence in the study was not completely reliable, since the short study duration, so the incidence resulted lower than literature values located between 20% (Spinelli 2003) and 30% (Fabiano & Piegai 2007), the latter value seems more reliable, since obtained in a follow up work study.

The damage percentage was significantly reduced in the sub-area harvested by chainsaw with felling frame. The damage reduction could be explained by an improved directed tree falling and bunching, since trees were addressed with butt ends to the winching corridors, reducing damages in subsequent winching operations. In a large survey carried out in Italy on small tree extraction by forest winches and small cable yarders the proportion of damaged trees resulted 15% of residual stands (Verani 1995). This percentage is in line with 16% stand damage obtained by the comparison of different working systems in Austria (Limbeck-Lilienau 2003). While in the Nordic countries the percentage of damaged trees in thinning operations remains under 4-5% of the residual stand (Siren 2001). These values are extremely low when compared to North America thinning reality, with damages on 20% of residual trees, during skidding operations (Siren, 2001). However in our study was carried out a selective thinning treatment, so without a geometric pattern, this complicated winching operations and therefore increased the risk of damages.

In thinning cost calculations was considered a directed tree felling, carried out by a single operator with chainsaw and felling frame and extraction performed by a three operators crew with a farm tractor and a forest winch. The gross productivity was obtained by increasing the effective working times in felling and skidding operations by 20% and 30% respectively, as suggested in results and literature (Spinelli et al. 2003; Fabiano & Piegai 2007). From these assumptions resulted costs of whole trees at roadside (€/t) as shown in Table 6.

Table 6: Thinning operations cost resulted from the field study

	Hourly machine cost [€ h^{-1}]	Hourly labour cost [€ h^{-1}]	Operation cost [€ h^{-1}]	Gross productivity [t h^{-1}]	Total cost [€ t^{-1}]	Percentage of total cost [%]
Felling	2,87	16,00 (1)	18,87	3,42	5,52	17%
Winching and skidding	14,58	44,00 (3)	58,58	2,23	26,26	83%
Total					**31,78**	

( ) Number of operators

As previously calculated, market price of whole trees at landing resulted 23 €/t, so using recorded productivities in cost calculations, the thinning practice resulted unsustainable from economic point of view. As well, considering different skidding distances, biomass harvesting cost remains over the whole tree market price (Fig. 15) with consequent economic failure.

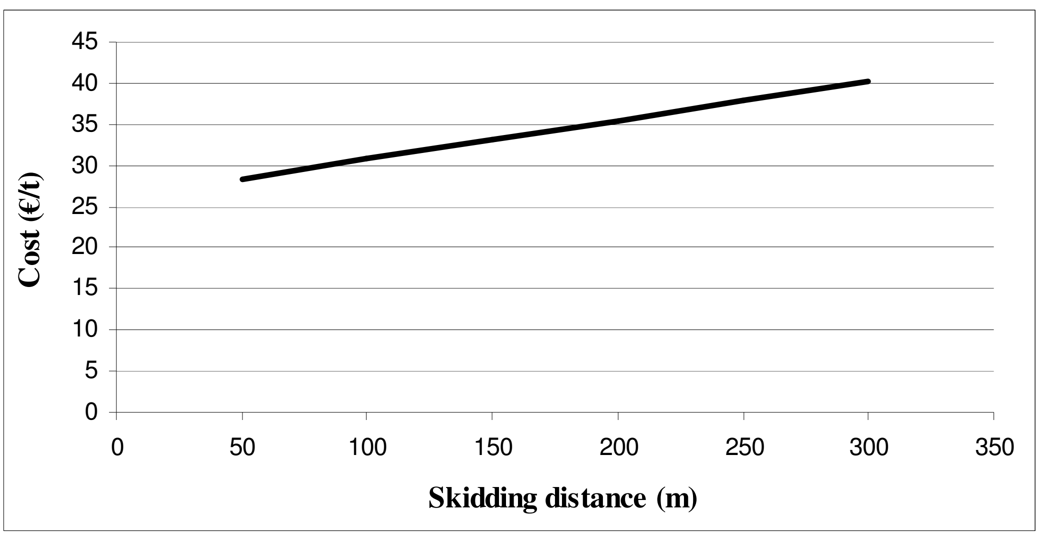

Figure 15. Whole tree harvesting cost (€/t) in function of skidding distance (winching distance 23 m).

Based on machine masses, fuel consumption recorded in the study and calculated lubricant consumption was carried out an inventory of CO_2 emissions during harvesting operations as in Table 7.

Tab. 7: Kg Co2 eq /MWh emissions resulted in thinning operations

		Direct emission	Indirect emission		Total emission	
			Fuel production	Machine production		
Chainsaw and felling frame	Mixture	0,25	0,01	0,001	0,28	9%
	Lubricant		0,01			
Farm tractor and forest winch	Diesel	2,38	0,09	0,491	2,98	91%
	Lubricant		0,02			
		81%	19%		3,26	

STUDY IV

Materials and methods

The study area was located in the community of Ängelholm (56°15'N, 12°51'E) southern of Sweden. The stand was dominated by birch (*Betula ssp.*) (93.3%) and with minor contribution of Norway spruce (*Picea abies*) (6.7 %), GYL (ground conditions), according to Swedish classification were 111. The stand was previously subjected to PCT. For the experiments 12 study units, each corresponding to at least 30 minutes of effective harvesting time were identified and marked. Seven of the study units were sized to 50×20 m and five to 40×20 m. In each study unit a centre line (strip road centre) was marked out with a start and stop sign. All study units were characterized by measuring the diameter at breast height (dbh), diameter at stump height and height of sample trees in nine circular areas (each 28.3m²) systematically placed along the centre line. The stem volumes of trees were calculated using the Andersson's (1954) (dbh ≤ 5 cm) and Näslund's (1947) (dbh > 5 cm) functions. The 12 study units were then paired in six blocks from similarities of trees ha^{-1} and average dbh (Table 1). The time study had a randomized design with six blocks, each representing a type stand with a varying number of trees per ha and average tree size. The treatments and harvesting order were assigned to each block and parcel by randomization. The effects were assessed by analysis of variance using the two-way ANOVA model:

$$y_{ij} = \mu + t_i + b_j + e_{ij}$$

were μ is the overall mean, t_i the treatment main effect, b_j the block main effect and e_{ij} the random error term. The differences were considered statistically significant if the Type III test indicated p-values inferior to 0.05. The stands structure (Table 1) analysis pointed out significant differences between blocks, but not between treatments (p>0.05).

Table 1. Characteristics of the study units used in experiments

	Block								
	1	2	3	4	5	6	Average	p-value Block	p-value Treatment
Dbh*(cm)	10.9	9.1	9.7	9.4	8.4	8.8	9.4	0.009	0.261
Height (m)	11.6	10.9	11.0	10.8	10.5	10.8	10.9	0.084	0.423
Density (trees ha^{-1})	2493	3023	2631	3278	3082	2768	2879	0.050	1.000
Basal area (m^2 ha^{-1})	26.1	22.1	24.1	26.1	19.0	19.0	22.8	0.065	0.753
Stem volume**(dm^3)	63	42	47	46	35	40	46	0.036	0.203
Total stem volume (m^3 ha^{-1})	157	128	125	152	107	109	130	0.036	0.269
Total biomass volume (m^3 ha^{-1})	210	168	170	212	141	143	174	0.034	0.274
Total biomass (o.d. t ha^{-1})	112	89	88	108	74	76	91	0.026	0.249

[*]Arithmetic mean diameter at breast height, [**]Stem volume incl. bark.

Significantly difference if $p \leq 0.05$.

The base machine used in experiments was a eight wheeled GREMO 950 HPVR harvester with a mass of 13.970 kg, a width of 2.6 m, and a maximum boom reach of 10 m (crane model: LOGLIFT 181 V). In the pulpwood treatment a LOGMAX 4000B harvester head (mass 625 kg) was used and for energy wood (whole tree) harvesting a SILVATEC felling head (mass 480 kg) was used. The same machine operator carried out both harvesting treatment and he had six years of experience in thinning operations operating similar base machines. He was experienced with the SILVATEC felling head but had no experience with the LOGMAX harvester head, however he used similar harvesting heads in past.

The thinning operation was performed selectively from below and the operator decided which trees to be harvested. After harvesting the remaining stand should contain about 1400 trees ha^{-1}. In pulpwood harvesting trees located on the side of the strip roads were pulled over the strip road and processed on the opposite side leaving branches and tops of processed trees on the strip road area. The pulp wood logs were cut in lengths ranging between 310 cm and 455 cm, with a top diameter of at least 5 cm. The smallest tree felled in pulpwood harvesting had a diameter at breast height of 3.5 cm, trees too small sized for pulpwood were left into the stand as whole trees. In energy wood harvesting whole trees were felled and bunched along the strip road with the butt ends pointing towards the strip roads. During the time study 22.8 m^3 o.b. of pulpwood and 40.1 solid m^3 (20 o.d. tonnes) of energy wood were harvested.

The operational work was measured by a frequency time study and the work was divided into seven work elements (Table 2). Every seven seconds the present work element was registered and if two elements were overlapping the element with higher priority was registered (Table 2). Besides the frequency time measuring the total time was recorded with a stopwatch. The same researcher performed all time collections. Moreover, during energy wood harvesting, in each crane cycle was recorded the number of accumulated trees.

The time studies were performed during September 2008. All study units were harvested from the east to the west and there were no disturbances such as sun light or rain. During harvesting of the stand n. 4 the accumulating function of the SILVATEC felling head did not worked, so the resulting time consumption was excluded from productivity model calculations. Other minor delays occurred during the whole experiment: some breakage of saw chain and hydraulics hoses.

Table 2. Work elements in a work cycle

Work element	Description		Priority
	Pulp wood	**Energy wood**	
Boom out	Starts when an empty crane moves towards a tree to be harvested and stops when the tree has been reached.	Starts when an empty crane moves towards a tree to be harvested and stops when the tree has been reached.	1
Felling	Starts when the tree has been reached and stops when the tree has been felled.	Starts when the first tree has been reached and stops when the last tree has been felled (moving to next tree included).	1
Boom in	Starts when the tree has been felled and stops when the harvesting head starts processing.	Starts when the last tree in the crane cycle has been felled and stops when trees have been dropped on the ground (including fixing the bunch).	2
Processing	Starts when the harvester head starts to process a tree and stops when the last piece has been dropped.	-	1
Moving	Starts when the base machine wheels are turning and ends when the base machine stops.	Starts when the base machine wheels are turning and ends when the base machine stops.	3
Miscellaneous	Other activities e.g. trees are dropped and then picked up again.	Other activities e.g. trees are dropped and then picked up again.	4
Delays	Time not related to effective work time e.g. personal breaks, repairing.	Time not related to effective work time e.g. personal breaks, repairing.	5

After harvesting, in the energy wood treatments, the diameter at stump of each harvested tree was measured. Subsequently all trees harvested were hauled to road side and then chipped into containers. The material was then transported to a power plant to measure bulk volume, mass, moisture content and energy content. The volume of harvested pulpwood on bark was calculated measuring the diameter in the middle and the length of each log and the volume was then reduced of 18 % to account the bark content. In each study unit, in two transactional rectangle surfaces (5×20 m) and perpendicular to the strip road centre, damages on remaining trees were measured and grouped in dimensional classes according to size and location (damages in stand and strip road border trees).

Figure 1: Harvester head (on the left) and AFH accumulating felling head (on the right).

System analysis

Stumpage prices were based on year 2009 market prices for Sweden: the roadside price of pulpwood u. b. for birch was 29 € m^{-3} and the energy wood price at roadside (tree parts) of 13.4 € MWh^{-1} (32.3 € m³ $biomass^{-1}$). The harvested biomass was converted into energy using a heating value of 19.2MJ o.d.kg^{-1} and the moisture content of 50% (fresh woody biomass). The productivity of pulpwood forwarding were based on Nurminen et al. (2006) study giving an average value of 13.49 m³ E0H-hour. The productivity of energy wood forwarding was assumed 15% lower than pulpwood forwarding, as suggested by Heikkilä et al (2006), noticing a productivity in forwarding whole trees 10-20% lower than forwarding delimbed wood. The productivity calculations were assumed for a forwarding distance of 100m and a haulage load size of 8 solid m^3. The productivities per effective hour were converted to gross-effective productivities using coefficient 1.3 in harvesting and 1.2 in forwarding (Laitila 2008). The operating costs of the harvester were set to 80 €/E_{15}h and for the forwarder to 60 €/E_{15}h. The net values of removals in all harvesting conditions were calculated. A sensitivity analysis was carried out, considering different pulpwood harvesting productivities and market prices.

Volume availability

The availability of pulpwood and energy wood from birch thinning in Sweden was estimated using first thinning type stands from Bredberg (1972). In the analysis were included Birch dominated stands aged from 24 to 35 years in three stand conditions (A-B-C), representing different stem dimensions and densities. Only trees with a dbh $\geq$ 5cm were used in calculations and the suggested thinning “priority” (from below) based on DBH class and future stand position from Bredberg

(1972) were used. For each stand were simulated three different intensity of thinning, harvesting 20% , 30% and 40% in Basal area. From inventoried data (diameter at stump, DBH, bark thickness, height, length of roundwood stem) were calculated the stem proportions of pulpwood and energy wood in each diameter class. The minimum stem diameter under bark was set to 5 cm and the usable logs length range between 3 and 5.5 m. The pulpwood stem volume under bark was calculated using diameter at middle of the length of a pulp wood piece and the cone volume formula. Biomass dry weight in stem, branches and needles was calculated using Marklund's (1987) functions and were converted into solid volume by using stem basic densities and values for crown biomass by Hakkila (1978).

Results

Field study

The initial stand had a higher total biomass volume per ha in the pulpwood treatment than in the energy wood (Table 3). Stand removals showed only minor differences in harvested basal area, tree densities and stem sizes between treatments (Table 3). The mean stem size was 40 dm^3 in energy wood and 37 dm^3 in pulpwood harvesting, however the harvested volume per ha was 2 times as high in energy wood harvesting than in pulpwood harvesting, depending on the added volume in tops and branches. The average width of strip road was 4.1 m. The percentage of damaged trees was higher in pulpwood harvesting, however these figures were not statistically different ($p=0.064$).

Table 3. Stand and tree properties

Initial stand				
		P*	E*	p-value
Dbh[1)]	(cm)	9.5	9.3	0.261
Height	(m)	11.0	10.9	0.423
Density	(N trees ha^{-1})	2879	2879	1.000
Basal area	(m^2 ha^{-1})	23.0	22.5	0.753
Stem volume[2)]	(dm^3)	47	44	0.203
Total stem volume	(m^3 ha^{-1})	134	125	0.269
Total biomass volume	(m^3 ha^{-1})	180	168	0.274
Total biomass	(o.d. t ha^{-1})	94	88	0.249

Removal				
Harvested Basal Area	(%)	39	44	0.168
Harvested trees	(N ha^{-1})	1297	1386	0.281
Average stem volume removal	(dm^3)	37	40	0.385
Harvested volume[3)]	(m^3 ha^{-1})	39	77	0.000
Harvested mass[4)]	(o.d. t ha^{-1})	21	38	0.000
Stand after harvesting				
Strip road width	(m)	4.0	4.1	0.544
Strip road tree damage	(%)	2.2	2.0	0.878
Stand tree damage	(%)	7.2	2.8	0.144
Total damage	(%)	9.3	5.0	0.064

* P= pulpwood , E= energy wood [1)]Arithmetic mean diameter at breast height, [2)]Stem volume incl. bark., [3)]In E the biomass solid volume while in P the pulpwood volume o.b., [4)]In E the biomass dry mass while in P the pulpwood o.b. dry mass. Significantly difference if $p \leq 0.05$

Time study

In the time study analysis the highest percentage of time consumption (E0H) was noticed in boom out and boom in phases, respectively 37%-28% of energy wood and 28%-26% of pulpwood harvesting (Table 4). Machine moving took 11% of E_0h in both methodologies, the percentage analogy was mainly related to the same strip road working pattern. The share of felling and collecting took 24% in energy wood and 9% in pulpwood harvesting. The proportion of multi tree handling was 58% of energy wood harvested trees and the average bunch size contained 1.88 trees. The share of delays was under 3% in both methodologies.

Table 4. Time consumption per work element and treatment

	Time per tree (s, SD)		Effective time percentage	
	P	E	P	E
Boom out	8.4 (1.1)	6.6 (1.2)	27.8%	37.0%
Boom in	8.0 (1.2)	5.0 (1.2)	26.3%	28.1%
Felling and collecting	2.7 (0.4)	4.2 (0.7)	8.8%	23.6%
Processing	7.1(0.8)	- -	23.3%	-

Moving	3.4(0.5)	1.9 (0.3)	11.3%	10.9%
Miscellaneous	0.8(0.3)	0.1 (0.1)	2.5%	0.5%
Effective total time (E_0h)	30.3(2.8)	17.9 (3.1)		

The average number of trees harvested per effective hour (E_0h) was 205 and 120 in energy wood and pulpwood harvesting respectively. The average effective productivity was 11,2 $m^3E_0h^{-1}$ in energy wood harvesting, and 3,7 m^3 E_0h^{-1}in pulpwood harvesting. For both treatment, the productivity was higher at higher average harvested stem volume (Fig. 2). The difference between treatments productivities were significant ($p<0.0001$).

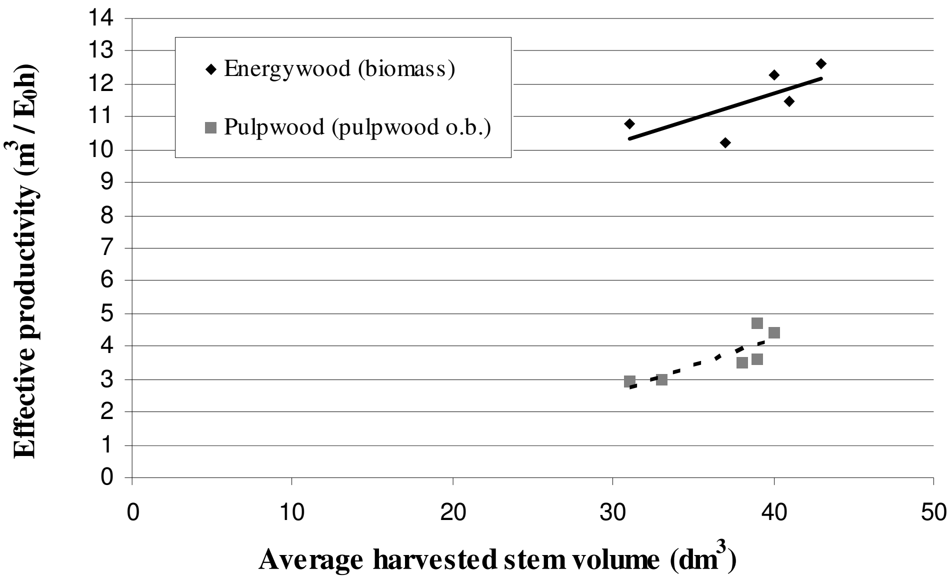

Figure 2. Effective Productivity as a function of harvested tree size

Table 5. Regression models for pulpwood and energy wood productivity

y=a+bx

y=productivity m^3/E_0h

x = removal average stem size dm^3

a= constant

b= parameter estimate

	Pulpwood			Energy wood		
	Coefficient	Pr > t	R²	Coefficient	Pr > t	R²
A	-2,275	0,324		5,606	0,194	
B	0,163	0,042		0,153	0,177	
			0,686			0,507

<u>System analyses</u>

The gross and effective income (values at landing) for harvested stands is shown in Table 6. The harvesting cost represented 60% and 84% of logging cost in energy wood and in pulpwood system respectively. The net income, including harvesting and forwarding, was negative in all pulpwood stands, while in energy wood stands net income was throughout positive and increased with biomass removal (Fig. 3).

Table 6. Removal intensities and corresponding economic revenues

		P*	E*
Harvested Basal Area	(%)	39(6)	44(6)
Harvested volume[1)]	(%)	32(4)	77(9)
Gross Income	(m^3 ha^{-1})	937(120)	2.382(283)
Net Income	(€ ha^{-1})	-406 (198)	1.187 (196)

* P= pulpwood , E= energy wood [1)]In E the biomass solid volume while in P the pulpwood volume u.b. ( ) Standard deviation

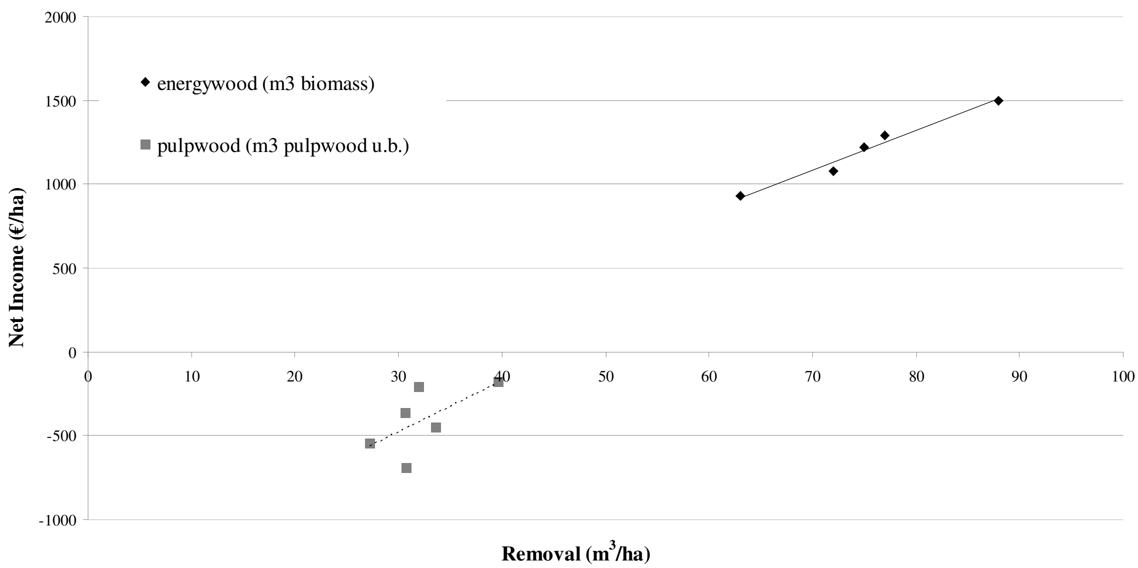

Figure 3. The net income (€ ha^{-1}) as a function of stand removal

<u>Volume availability</u>

The harvesting simulation in type stands pointed out that pulpwood removal exceed 30 m^3 ha^{-1}, considered nowadays the minimum volume for profitable pulpwood harvesting, only in the best stand condition (A stands), and harvesting at least 30% of basal area (Table 7). The proportion of residual biomass in 78% of the cases was over 50% of total available volume. In average the removal of pulpwood was 17 m^3 ha^{-1} and the residual biomass 28 m^3 ha^{-1}, so pulpwood represented 37% of total harvestable volume. In all stand conditions the proportion of pulpwood increased with thinning intensity and stem size.

Table 7. Characteristic of birch dominated type stands for thinning (Bredberg 1972) and the properties of harvest at different density of removal.

Properties	Type stands								
	X (A)			Y (B)			Z (C)		
Age (years)	35			30			24		
Stand density (trees ha^{-1})	1740			2650			3590		
Dbh[1] (cm)	13.9			10.4			9.3		
Height (m)	11.6			9.4			8.7		
Basal area (m^2 ha^{-1})	29.9			25.1			21.8		
Stem volume[2] (dm^3)	99			45			33		
Total stem volume (m^3 ha^{-1})	172			120			117		
Tree biomass volume (dm^3)	134			63			45		
Total biomass volume (m^3 ha^{-1})	234			166			161		
Removal (% of basal area)	20	30	40	20	30	40	20	30	40
Density (trees ha^{-1})	680	880	1110	1170	1460	1630	990	1460	1880
Dbh[1] (cm)	9.7	10.7	11.4	7.4	8.0	8.6	6.3	6.9	7.4
Stem volume[2] (dm^3)	40	52	61	19	23	29	13	15	18
Pulpwood volume (m^3 u. b. ha^{-1})	17	30	46	7	15	24	0	5	12
Biomass volume (m^3 ha^{-1})	36	58	86	28	43	60	16	30	45
Biomass/Pulpwood volume	2.1	1.9	1.9	4.0	2.9	2.5	∞	6.0	3.8

[1]Arithmetic mean diameter at breast height, [2]Stem volume included bark.

Using the current market prices was calculated the gross income of type stands in different harvesting conditions (Fig. 4). In average the gross income was 501 € ha^{-1} for pulpwood and 1.447 €

ha^{-1} for the whole biomass as energy wood, so pulpwood represents in average 33% of energy wood income.

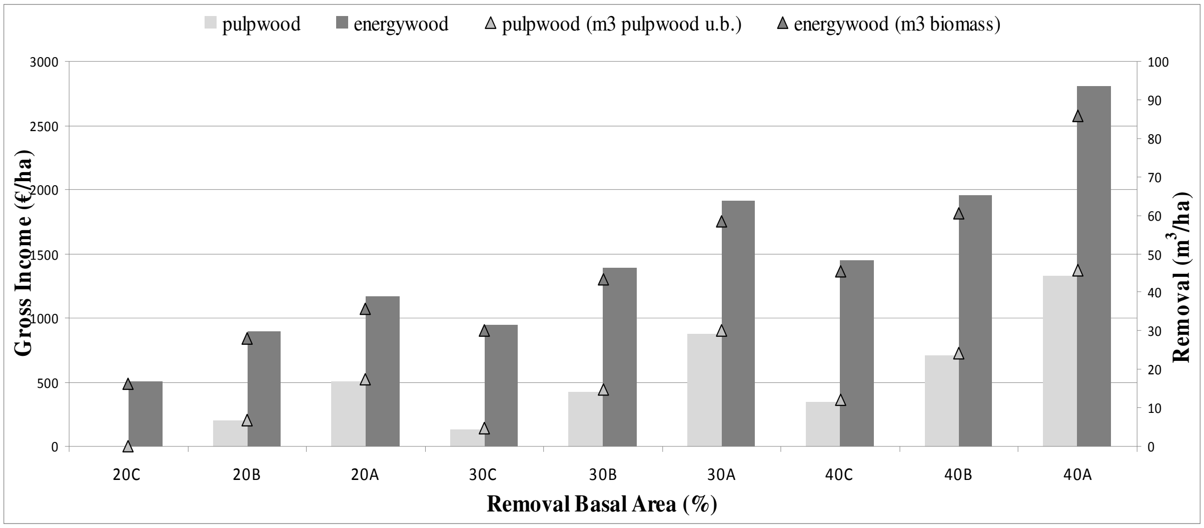

Figure 4. The gross income (€ ha^{-1}) for different percentage of removed basal area and volumes.

Discussion

The whole tree harvesting in thinning of young birch stands showed to double the removal of biomass volume in comparison to pulpwood harvesting, when the mean stem volume of harvested trees was 40 dm^3. The simulation of first thinning in different stands confirmed the field study results and showed an increase of pulpwood/biomass volume ratio for higher thinning intensity and larger stem volume, these results were in accord to simulations of Heikkila et al. (2007) in Scots pine dominated stands. The proportion of biomass could be further increased if trees under 5 cm dbh were included in the simulations.

The time study was addressed to an analysis of productivity difference between the two harvesting methods, considering stem sizes from 31 to 44 dm^3, so the results are not suitable in different conditions. The average effective productivity recorded in whole tree harvesting was three times higher than in pulpwood harvesting. The results of time study pointed out that removal stem volume had the greatest influence on the effective productivity in both harvesting methodologies as found in other studies related to thinning harvesters (Eliasson 1998). The obtained regression trends were in line with other models (Figure 5), using similar machines and harvesting methodologies (Kärhä et al. 2006, Kärhä et al. 2004). Comparing the average effective productivity recorded in whole tree harvesting with the value obtained by Kärhä et al. (2006) function, the difference was under 2%, indicating an high reliability of found values. The bunch size, using the accumulating felling head, remained in average below two stems, meaning that the majority of trees were felled singly, as noticed by Kärhä et al. (2006) when the removal stem size was over 35 dm^3.

However the average effective productivity in pulpwood harvesting was 31% lower than values provided by Kärhä et al. (2004) function, indicating a possible under estimation, that should be related to the limited experience of the operator with the LOGMAX harvester head, since the experience has a proven influence on harvester operator productivity.

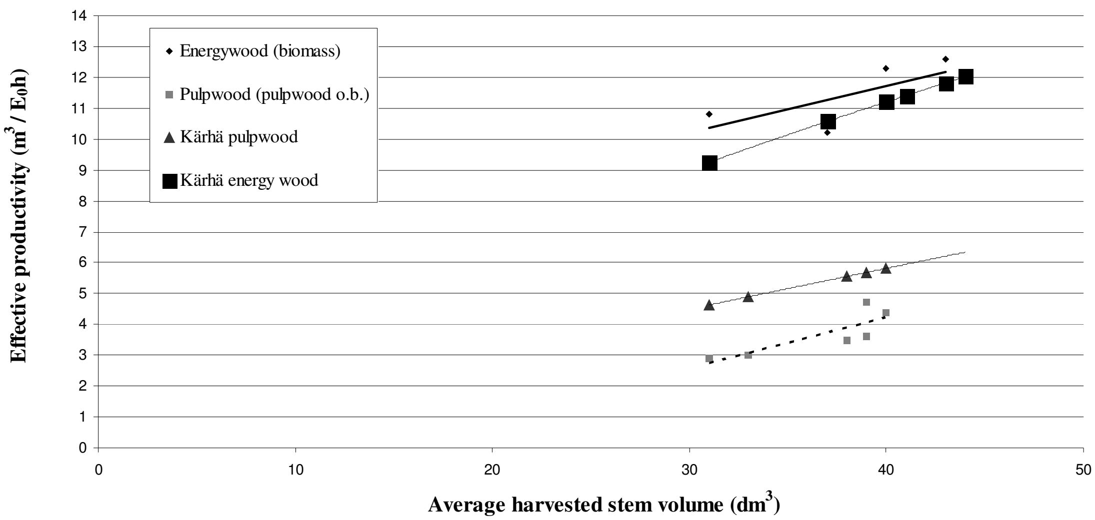

Figure 5. Effective Productivity as a function of harvested tree size. Comparison of the found models with function by Kärhä et al. 2004 (Kärhä pulpwood) and Kärhä et al. 2006 (Kärhä energy wood).

The time study length was not enough representative of delays to provide information about operating productivity coefficients, instead these coefficients are usually obtained in long term analysis (Kuitto et al. 1994), so for the subsequent economic calculation was supposed the same literature value for the different harvesting methodologies.

The economic difference between the two thinning systems was assessed through a sensitivity analysis, assuming an increase in pulpwood harvesting productivity or roadside price in order to reach the same profitability of energy wood system in studied stand conditions.

Assuming as constant pulpwood and energy wood roadside prices, the pulpwood harvesting productivity should increase of 80% in order to reach the same profitability of energy wood system (Figure 6).

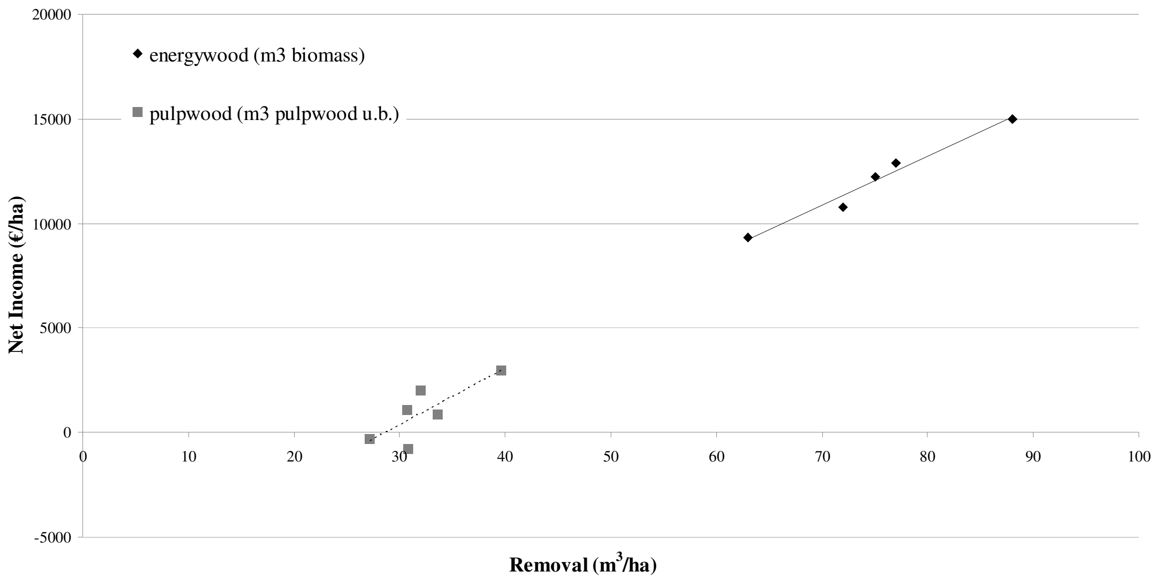

Figure 6. The net income (€ ha^{-1}) as a function of stand removal, assuming an increase of 80% in current pulpwood harvesting productivity.

Otherwise, assuming as constant found harvesting productivities, it is needed an increase of 20% in current pulpwood price to reach the same energy wood net income (Figure 7).

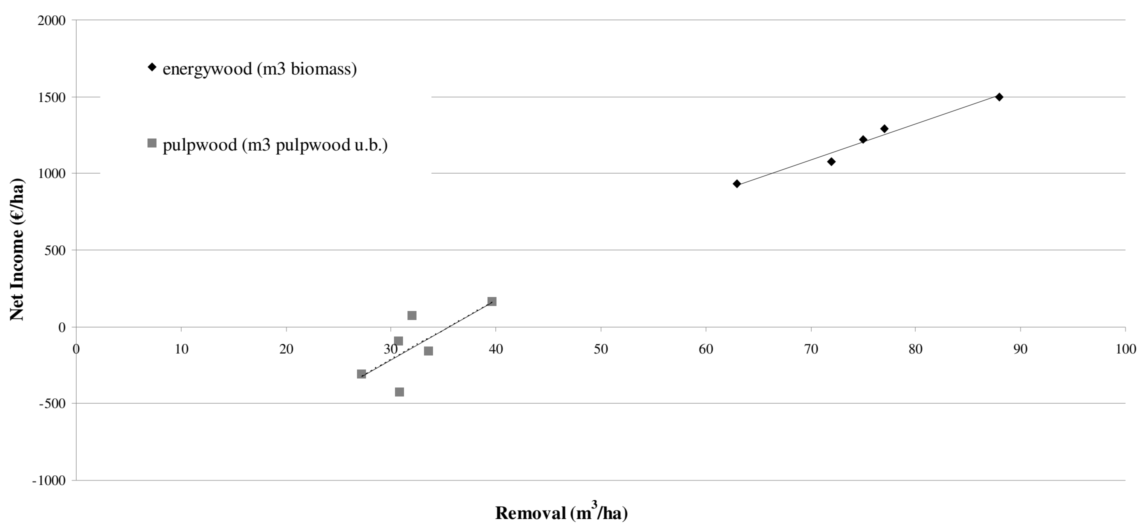

Figure 7. The net income (€ ha^{-1}) as a function of stand removal, assuming an increase of 20% in current pulpwood roadside price.

Silvicultural results showed only minor differences between the two different harvesting methodologies, anyway the damage percentage in pulpwood thinning exceeded 5%, considered the acceptable limit for thinning operations in the Nordic Countries (Niemela et al. 1997). Moreover the stand were pre cleared, so was expected to find a better silvicultural condition.

The economic results of the small scale and large scale thinning allowed a comparison of whole tree harvesting cost at roadside (€/t) in the Swedish and Italian reality. The comparison was carried out using Italian thinning results and felling productivities obtained in energy wood harvesting in Sweden integrated by a whole trees forwarding model (Laitila et al. 2007), assuming a forwarder payload of 8.5 tonnes, distances between 50 and 300 m and removals from 30 to 75 m^3/ha. In the large scale thinning was considered an harvester cost of 80 €/E_{15}h and for a medium sized forwarder 60 €/E_{15}h.

From the comparison of the two realities resulted that in the Nordic Countries a two machines working system (harvester and forwarder) allows energy wood costs from 38% to 49% inferior to felling and extraction with small scale mechanization in Italy (Fig. 8).

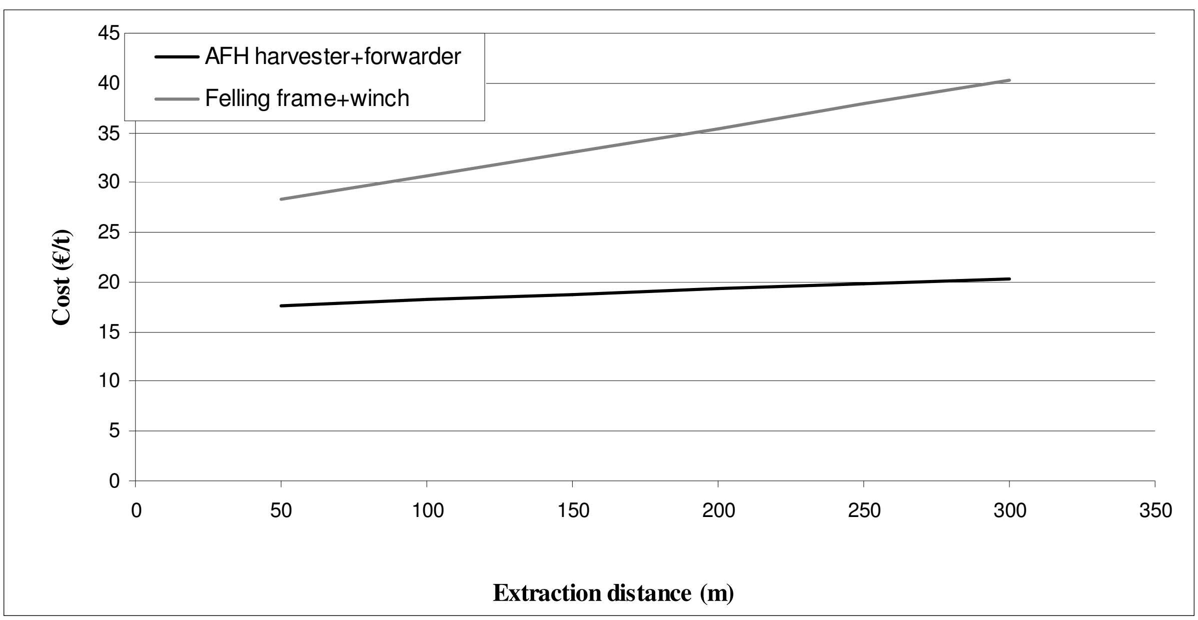

Figure 8: Comparison of whole tree harvesting cost in a first thinning (Moisture Content 55%) in function of extraction distance, using "small scale" (chainsaw with felling frame and forest winch) and "large scale" equipment (AFH harvester and forwarder).

STUDY V

Study Va

Materials and Methods

The area considered in this study was a Short Rotation Coppice with two years cutting cycle. The plantation area contained two stands, one planted with *Populus x euroamericana* clone “Monviso” and another with *Robinia pseudoacacia* L., realized in singles rows with a regular scheme (0,6 m x 3 m; 1m x 3m) the stands were located in the municipality of Montalto di Castro (VT) (42°21'N, 11°39'E) on marginal agricultural land, these areas were excluded from tradition wheat cultivation, since the low land fertility. The SRC was not irrigated or fertilized during the growing cycle. The plantation was situated on a flat ground (I class of slope) with large presence of stones. The two plantations were felled in December 2007 with a motor manual felling using two machines, a chainsaw (STIHL 025 2.3 kW) with felling frame and a cleaning saw (STIHL 048 2.2 kW) (Figure 1). In the field study were randomly selected 10 rows divided in two plots (each plot of five rows), so one plot was harvested with chainsaw and the other with cleaning saw, for a total of 300 trees per methodology. Trees were felled with tree tops perpendicular to each plantation row, to simplify the subsequent extraction with a farm tractor equipped with frontal loader and subsequent comminution at roadside.

After the winter felling, trees were left for 104 days on the ground to reduce moisture content.

A sample of 20 trees was extracted from felled trees and measured in diameter at stump, stem height, stem and branches mass.

On a sub-sample of 10 trees were collected small discs (10 cm in length), from base, middle height and tree top. The discs were dried in stove at 103°C, for basal density and moisture content calculations (UNI 9091/2). The disc sampling was repeated on felled trees after field seasoning, at harvesting time. The difference of moisture content at the beginning and at the end of seasoning period were compared by a T-test ($p<0.05$).

During felling operation were recorded effective work times using three chronometers. The same operator performed the two different felling methodologies.

The effective work time was divided into the following time elements:

Row cutting: time between the beginning of cutting operation on the first tree to the complete felling of last tree in the row.

Accessory: other times required by the effective work (eg. end row turning).

On each row were measured:

- Number of trees
- Diameter at stump of 20 trees.

From effective work time recording was calculated single tree felling time. Effective productivity was given by the ratio of product (N. trees, t, o.d.t) and effective work time (E_0h).

Net times and effective productivities were compared by ANOVA statistical analysis ($p < 0.05$) to find significant differences.

Diameters at stump comparison allowed to confirm the absence of significant difference between the rows assigned to the different felling methodologies by T-test ($p < 0.05$).

Figure 1: Felling of two years poplar trees by chainsaw with felling frame (on the left) and cleaning saw (on the right).

Figure 2: Felling of two years *Robinia pseudoacacia* trees by chainsaw with felling frame

The motor-manual-felling system was compared to an harvester-chipper head (SPAPPERI) powered by farm tractor (150kW), reverse driven in the stand (Figure 3), the harvester head performed the cutting by two circular saws and contemporary chipping by a disc chipper, blowing up the produced chips directly in two 15 m^3 trailers applied to farm tractors (80 kW) in farm transportation (500 m distance).

Figure 3: Harvesting of poplar two years SRF by tractor driven harvester-chipper head.

The machine effective work time per row (E_0h) was recorded on a total of 10 rows. In each row was counted the number of harvested trees, so effective productivity was determined, at the same time were measured delays included in $E_{15}h$.
The mechanized harvesting system was compared with the cutting performed with cleaning saw, a field seasoning for three months, the collection of trees using a farm tractor (70 kW) with frontal fork loader, subsequent chipping at landing using a small chipper powered by a farm tractor (90 kW), and farm transportation with farm tractor (80kW) and trailer.
In system comparisons, data recorded in the field study were integrated by productivity achieved in similar conditions in small tree extraction and chipping operations (Sims & Venturi 2004; Spinelli & Hartsough 2001).
In economic calculations was assumed a value of 400€ for a clearing saw, 220.000€ for farm tractor and harvester-chipper head, 45.000€ for farm tractor with frontal loader, 60.000€ for farm tractor and chipper, 80.000 € for farm tractor and trailer. Assuming a lifespan of 2.000 hours for the cleaning saw and 10.000 hours for tractors (Hippoliti 1997). Using Hippoliti formula (1997) machine costs were calculated, so adding labor costs derived from National Contract was calculated the operation costs and energy chips harvesting costs.

Results

The average stand and mean tree characteristics for the two SRC plantations are shown in Table 1. The analysis of biomass distribution in whole trees pointed out a relevant percentage of total biomass coming from branches, representing 30% in poplar and 44% in robinia stand. In tree biomass were not included leaves, since this component usually remain on the ground during a winter coppicing.
The moisture content at felling time was too high for a direct biomass combustion, so suggesting a biomass seasoning to maximize energy conversion processes.

Table 1: Stand and average tree characteristics (standard deviation between parenthesis).

	Populus	*Robinia*
Density (tree ha^{-1})	5.556	3.333
Stump diameter (cm)	5.1 (0.52)	3.7 (1.40)
Height (m)	4.08 (0.25)	2.70 (0.53)
Stem mass (kg)	2.00	1.64
Stem basal density (o.d. kg/m^3)	384	529
Whole tree mass (kg)	2.87	2.95
Moisture content (%)	50	45
Whole tree dry mass (o.d. kg)	1.44	1.62
Total dry mass (o.d. t ha^{-1})	8.0	5.4

A significant reduction of moisture content was achieved through the whole tree field seasoning, so reaching values close to the recommended to use biomass in small boilers for heat production (35%).

Table 2: Moisture content (M.C.%) at the felling time and after three months of field seasoning, different letters in each row show statistical significant difference (p<0.05).

	M. C. 19-12-2007 (%)	M. C. 03-04-2008 (%)	p-value
Populus	50a	40b	<0.0001
Robinia	45a	29b	<0.0001

The average stump diameter was similar in the two felling areas (p = 0,783), resulting 5.1 cm for chainsaw with felling frame and 5.2 cm for cleaning-saw, so we could assume that work time comparison was carried out in similar stand conditions.

Analysis of working time (Table 3) pointed out a significant reduction effective felling time using the cleaning saw in felling operation. Cutting time was not significantly different, but there was a significant difference in accessory times, related to the machine movement to pass from a tree to another, causing a significant increase of effective time per tree.

The increase of accessory times in chainsaw operation significantly affected the felling productivity, causing a 25% reduction in number of felled trees per hour, if compared to cleaning saw. Comparing average stump diameter and felling time were not found significant correlations, this can be explained by the small variation in diameters as noticed by the low standard deviations.

Table 3. Effective time elements in felling operation (cmin) and Effective productivity results, single operator crew, standard deviation between parenthesis, different letters in each row show significant difference ($p<0.05$).

	Effective time per tree		Time percentage	
	Felling frame cmin (s.d.)	Cleaning saw cmin (s.d.)	Felling frame	Cleaning saw
Felling	12.3 (1.7) a	10.9 (1.0) a	57.0%	43.0%
Accessory	9.0 (2.7) a	5.3 (2.5) b	66.8 %	33.2%
Effective time (E_0h)	21.6 (3.6) a	16.4 (3.1) b		
Productivity (Tree/E_0h)	284 a	378 b		
Productivty (t/E_0h)	0.8 a	1.1 b		
Productivity (o.d.t/E_0h)	0.4 a	0.6 b		

From times recorded during the mechanized operations were obtained results shown in Table 4. The gross productivity was largely influenced by delays occurred in tree felling, since frequently trees falling was not appropriate for in-feed chipper rollers, so trees were accumulated in front of the head, forcing to stop harvesting operations.

Table 4: Effective time per tree (cmin) and effective productivity results for chipper-harvester head driven by tractor.

Time (cmin) (E_0h)	3.0
Productivity (Trees/E_0h)	1976
Productivity (t/E_0h)	5.7
Productivity (o.d. t/E_0h)	2.8
Delays (% $E_{15}h$)	23%

Study Vb

Materials and Methods

A comparison of SRF poplar yields in two years plantation was carried out in optimal cultural conditions. The stands were located in a Regional Farm "Improsta" Eboli Municipality, in Campania Region (40°33'N, 14°58'E). In this farm were located five *Populus spp.* SRF plantations, realized with different clones of *Populus nigra* L. (P.n.) and *Populus x euroamericana* (P.eu.). The stand characteristics were measured in autumn 2009, at biennal cutting time. The plantations presented a regular distribution in a rectangular scheme (0.5 m x 3 m). Trees were located on a medium fertility flat terrain, all necessary cultural cares were carried out, including fertilization and irrigations.

In the plantation were sampled 10 trees per clone, on these were measured stump diameters and total stem heights. Using a certified scale were measured weights of stem, branches and leaves. Sample stem discs were collected from base, middle height and top to measure moisture content and to calculate fresh gravimeter density. Subsequently discs were dried in stove at 103°C, for basal density and moisture content calculations (UNI 9091/2).

In the field study were randomly selected 2 rows per clone and felled by chainsaw and felling frame. Trees were felled with tree tops perpendicular to each plantation row, to simplify the subsequent extraction with a farm tractor equipped with frontal loader and subsequent comminution at roadside.

During felling operation were recorded effective work times using three chronometers.

The effective work time was divided into the following time elements:

Row cutting: time between the beginning of cutting operation on the first tree to the complete felling of last tree in the row.

Accessory: other times required by the effective work (eg. end row turning).

On each row were measured:

- Number of trees
- Diameter at stump of 10 trees per row

From effective work time recording was calculated single tree felling time. Effective productivity was given by the ratio of product (N. trees, t, o.d.t) and effective work time (E_0h). At the same time were recorded short delays included in E_{15}h.

In the same plantations was compared the harvesting operation carried out by a self propelled forage harvester (JOHNDEERE 7350- 352 kW - mass 11.000 kg) equipped with a two circular saw harvester head (ALLASIA) and a drum chipper, the machine performed the cutting and contemporary chipping of trees, blowing up the produced chips directly on a 15 m^3 trailer applied to farm tractor (80 kW) used in farm transportation.

The machine effective work time was recorded in the same stand on 3 rows per clone, in each row was counted the number of trees, so productivity was determined, at the same time were measured delays included in $E_{15}h$.

The mechanized harvesting system was compared with the cutting performed with chainsaw, a field seasoning for three months, the collection of trees using a farm tractor (70 kW) with frontal fork loader, in this case was supposed chipping at landing using a small chipper powered by a farm tractor (90 kW), and farm transportation with farm tractor (80kW) and trailer.

In the system analysis field study data were integrated by productivity achieved in similar conditions in tree extraction and chipping operations (Sims & Venturi 2004; Spinelli & Hartsough 2001).

Figure 4. Harvesting of two years poplar SRF by modified forage harvester.

In economic calculations was assumed a value of 700€ for chainsaw with felling frame, 45.000€ for farm tractor with frontal loader, 60.000€ for farm tractor and chipper and 80.000€ for a farm tractor and trailer. Assuming a lifespan of 2.000 hours for the chainsaw and 10.000 hours for tractors. Using Hippoliti formula (1997) machine costs were calculated, so adding labor costs derived from National Contract was calculated the operation costs and energy chips harvesting costs.

For the mechanized harvesting was assumed a literature yard cost of 300 €/$E_{15}h$, including the harvester and two tractors with trailers and operators.

Results

In this study were analyzed optimal growth condition, obtaining the yield listed in Table 5 for five different poplar clones. The average production after two years was 18.1 o.d. t/ha, but yields showed a large variation for different clones, with a maximum of +32% (Muur) to a minimum of -22% (Grimminge), considering the same fertility and cultural practices. The results pointed out a possible correlation between clones basal density and tree sizes. As for trees of smaller size the annual growth rings are narrower, so containing a greater proportion of late wood, thus increasing the mass per volume unit. All clones considered in this study presented an high moisture content at autumnal felling, with an average of 48.8%, the deviations from the mean value were little (+5%, -6%), so this feature could be influenced by site conditions and species rather than by clone growth. The average branches percentage on total tree mass reached an average of 45%, although the percentage could reach 50% (clone Badolato). In the calculations of total biomass were excluded leaves, reducing possible nutrient removals, however the measurement of leaves showed that in average this component represents 10.5% of the poplar clones tree biomass.

Table 5: Stand and average tree characteristics per five different *Populus* clones (standard deviation between parenthesis).

Clone	*P.eu.* *I214*	*P. n.* *Limatola*	*P. eu.* *Grimminge*	*P. eu.* *Muur*	*P. n.* *Badolato*
Density (trees ha^{-1})	6.667	6.667	6.667	6.667	6.667
Stump diameter (cm)	5.5 (1.2)	6.0 (1.1)	4.4 (0.9)	6.4 (1.5)	4.8 (1.2)
Height (m)	5.2 (0.8)	5.2 (0.6)	4.0 (0.8)	5.3 (1.0)	4.0 (0.9)
Stem mass (kg)	3.0 (1.4)	3.9 (1.6)	1.9 (0.8)	4.0 (1.7)	2.0 (1.1)
Stem basal density (o.d. kg /m^3)	341	373	455	389	419
Whole tree mass (kg)	4.8	6.8	4.1	7.0	4.0
Moisture content (%)	51	50	48	49	46
Whole tree dry mass (o.d. kg)	2.4	3.4	2.1	3.6	2.1
Total dry mass (o.d. t ha^{-1})	16.0	22.6	14.1	24.0	14.0

Table 6: Effective time elements per tree in felling operation (cmin) and effective productivity results (single operator crew).

Clone	*I 214*	*Limatola*	*Grimminge*	*Muur*	*Badolato*
Felling	9.1	16.8	7.6	12.0	9.9
Accessory	5.4	12.0	8.1	8.1	14.6
Effective time (E_0h)	14.5	28.8	15.7	20.0	24.5
Productivity (Trees/E_0h)	413	208	382	299	245
Productivity (t/E_0h)	2.0	1.4	1.6	2.1	1.0
Productivity (o.d. t/E_0h)	1.0	0.7	0.8	1.1	0.5

In felling time distribution was noticed a 47% percentage due to accessory times, so largely influencing the resulting productivities. Cutting time was influenced by stump diameter and as a consequence by tree size (Fig. 5), as shown by the regression, however the limited variation of conditions did not allowed to extrapolate a general model for felling productivity calculations. Anyway only a small correlation between tree size and felling productivity was noticed (Fig. 6). The average felling productivity with chainsaw and felling frame resulted 1.62 t/E_0h, but with a large variation from 1 t /E_0h (clone Badolato) and 2.1 t /E_0h (clone Muur) (Table 6).

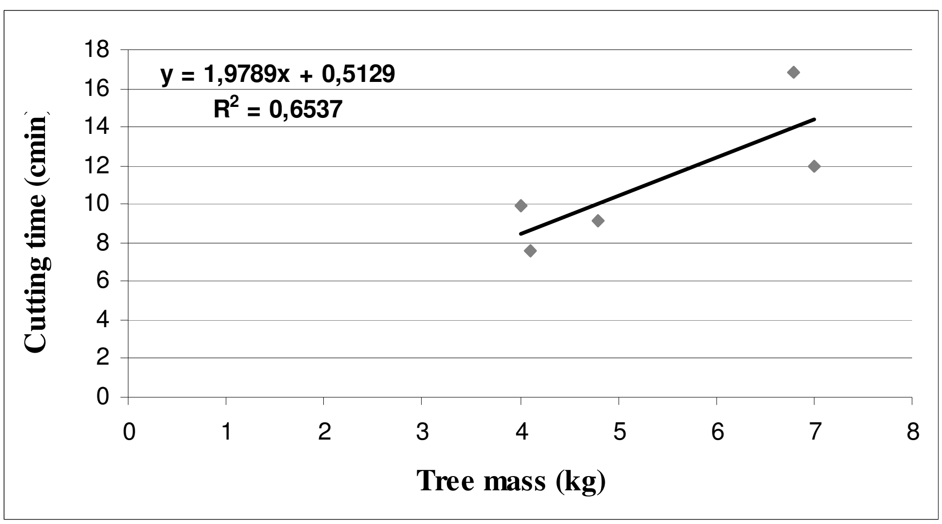

Figura 5: Cutting time (cmin) as function of tree mass

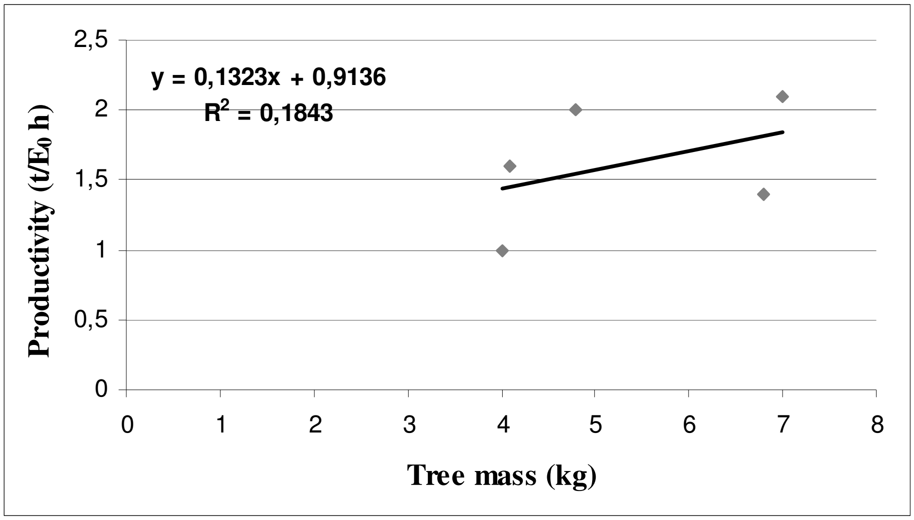

Figure 6: Effective felling productivity as function of tree mass.

During the felling operation with felling were recorded only small delays, so representing 8.7% of the total time (E_{15}h).

From times recorded during the mechanized operations were obtained results in Table 7. Delays occurred during the mechanized operations were mainly related to machine neck flooding, created by the fresh chips.

Table 7: Effective time per tree (cmin) and effective productivity results for chipper-harvester machine.

Effective time (cmin) (E_0h)	4.2
Productivity (Trees/E_0h)	1415
Productivity (t/E_0h)	9.6
Productivity (o.d. t/E_0h)	4.9
Delays (% E_{15}h)	7%

Discussion

The study allowed to obtain a valid information on biomass plantation on lands abandoned by traditional agricultural crops. The yield obtained in *Robinia pseudoacacia* biennial SRF plantation resulted 22% lower than in poplar clone stand, but the productivity was in line with literature yields on marginal agricultural lands (Paris et al. 2002). However, in higher fertility condition the species can reach yields of 7.7 o.d. t/ha /year, as suggested by Baldini & Berti (1990).

The yield of *Populus* SRF biennal plantation on marginal lands resulted 25% lower than values obtained for the same clone on fertile soils subjected to cultural cares, like fertilizations and irrigations, in similar climatic conditions (Verani & Sperandio 2006). So SRF poplar plantation yields are strongly affected by cultural input. These results were confirmed by the subsequent study, carried out in optimal cultural conditions, since yield increased 125% when compared to marginal land poplar productions. In the optimal plantation were used locally sourced poplar clones, thus maximizing species adaptation to local conditions. However cultural cares increased energy inputs, so the intensive SRF cultivation must be carefully evaluated from energetic and environmental point of view.

The biomass moisture content at harvesting time resulted too high for energy conversions, especially in poplar stands, this result suggested to start a field seasoning in order to avoid possible fermentations and material losses in subsequent chips storage and to maximize energy conversion efficiency.

The of whole tree field seasoning showed the possibility to achieve a significant reduction in moisture content during the winter season, lowering the moisture content to levels needed for efficient energy conversions. However, moisture content measurements should be integrated with related dry matter losses. At the same time climate parameters during the seasoning period should be characterized in order to identify correlations between moisture losses and local climatic factors.

The comparison of motor-manual felling methods pointed out that cleaning saw reaches the highest productivity, when felling trees of 5 cm (diameter at stump), resulting in a effective productivity 35% superior to the felling frame, this result was in accord with previous analysis of motor-manual felling operations (Staaf Wiksten and 1984). Accordingly a comparison carried out in Poland underlined the fatigue reduction when using a cleaning saw, if compared to a chainsaw on felling frame, allowing the operator to reduce energy consumption from 1558 kJ/h to 779 kJ/h (Grodecki et al. 1996). These considerations lead to suggest the cleaning saw when cutting diameter remains under 10 cm, otherwise the felling frame allow a better directed felling when subsequent biomass extraction is scheduled (Wiksten & Staaf 1984). These reasons suggested the cleaning saw in young stands cleaning operations, where the biomass is left in the stand, as usually in Sweden (Ligné 2004), while chainsaw with felling frame in pre-commercial thinning operations, when biomass is subsequently harvested, as usually in Finland (Laitila et al 2007). However the comparison of the two cutting devices should be repeated in subsequent plantation coppicing, in order to test cutting productivity when the number of sprouts per stump increased.

The felling operations performed in poplar stands in optimal growing conditions allowed to identify felling frame productivities for different tree sizes. The results in optimal growing conditions indicated that motor-manual felling productivity can be doubled in comparison to plantation on marginal conditions, since felling the same number of trees per hour the harvested tree biomass is doubled.
The mechanization of harvesting operations allowed to reach high productivities, if compared to motor-manual felling operations, however delays occurred in the field study suggest a possible improvement of felling apparatus, especially considering the harvesting in subsequent coppicing, when the number of sprouts per stump increase.
The analysis of cost pointed out that in case of low stand yield it is extremely difficult to reach economic sustainability of energy wood harvesting process, considering a chips selling price of 45 €/t. In the low yield plantation, the harvesting system based on the motor-manual felling reached the same cost of the completely mechanized system (Table 8 and 9). However, in the first harvesting system was reduced chips moisture content improving the energy conversion in small boilers used in Italy for farm heating. While in case of high yields an economical sustainability is reachable only in case of completely mechanized harvesting system (Table 9 and 10). However these costs do not included plantation cultivation.

Table 8. Study Va operation cost in SRF harvesting by motor-manual felling system (M.C. 40%).

	Hourly machine cost [€ h^{-1}]	Hourly labour cost [€ h^{-1}]	Operation cost [€ h^{-1}]	Gross productivity [t h^{-1}]	Total cost [€ t^{-1}]	Percentage of total cost [%]
Felling	2,60	16,00 (1)	18,60	1,00	18,60	%
Extraction	20,00	16,00 (1)	36,00	3,8	9,47	%
Chipping and farm transportation	52,00	32,00 (2)	84,00	3,5	24,00	%
Total					**52,07**	

( ) Number of operators

Table 9. Study Va operation cost in SRF harvesting by mechanized harvesting system. (M.C. 50%).

	Hourly machine cost [€ h^{-1}]	Hourly labour cost [€ h^{-1}]	Operation cost [€ h^{-1}]	Gross productivity [t h^{-1}]	Total cost [€ t^{-1}]
Felling, chipping and farm transportation	180	48,00 (3)	228,00	4,30	**53,02**

( ) Number of operators

Table 10: Study Vb operation cost in SRF harvesting by motormanual felling system (M.C. 49%).

	Hourly machine cost [€ h^{-1}]	Hourly labour cost [€ h^{-1}]	Operation cost [€ h^{-1}]	Gross productivity [t h^{-1}]	Total cost [€ t^{-1}]	Percentage of total cost [%]
Felling	2,87	16,00 (1)	18,87	1,49	12,66	31%
Extraction	20,00	16,00 (1)	36,00	6,00	6,00	15%
Chipping and farm transportation	52,00	32,00 (2)	84,00	3,75	22,4	54%
Total					**41,06**	

( ) Number of operators

Table 11. Study Vb operation cost in SRF harvesting in by mechanized felling system (harvester chipper) (M.C. 49%).

	Hourly machine cost [€ h^{-1}]	Hourly labour cost [€ h^{-1}]	Operation cost [€ h^{-1}]	Gross productivity [t h^{-1}]	Total cost [€ t^{-1}]
Felling, chipping and farm transportation	300	48,00 (3)	348,00	8,97	**38,79**

( ) Number of operators

Comparing emission in the whole supply chain it is marked the important role played by comminutiom, affecting the whole emission balance (Table 12 and 14). From an environmental point of view an higher plantation yield allowed higher harvesting productivities, so reducing time per unit of product and consequent emissions in motor-manual system (Table 14). The self-propelled machine (Table 15) largely increased emissions in comparison to a farm tractor equipped with an harvester-chipper head (Table 13), since the high fuel consumption was not compensated by an adequate increase in work productivity.

Table 12: Kg Co2 eq. /MWh emissions resulted in Va operation by motor-manual felling system

		Direct emission	Indirect emission		Total emission	
			Fuel production	Machine production		
Cleaning saw	Mixture	0,82	0,04	0,011	0,89	7%
	Lubricant		0,03			
Tractor and frontal loader	Diesel	2,75	0,11	0,356	3,24	26%
	Lubricant		0,02			
Tractor and chipper	Diesel	4,85	0,19	0,394	5,48	43%
	Lubricant		0,04			
Tractor and trailer	Diesel	2,24	0,09	0,64856	2,99	24%
	Lubricant		0,02			
		84%	16%		12,60	

Table 13: Kg Co2 eq. /MWh emissions resulted in Va operation by by mechanized harvesting system

		Direct emission	Indirect emission		Total emission	
			Fuel production	Machine productio n		
Tractor and harvester head	Diesel	4,55	0,18	0,606	5,38	52%
	Lubricant		0,04			
Tractor and trailer (2)	Diesel	3,64	0,14	1,148	4,97	48%
	Lubricant		0,03			
		79%	21%		10,35	

( )Number

Table 14: Kg Co2 eq. /MWh emissions resulted in Vb operation by motor-manual felling system

		Direct emission	Indirect emission		Total emission	
			Fuel production	Machine production		
Chaisaw with felling frame	Mixture	0,66	0,03	0,003	0,72	7%
	Lubricant		0,03			
Tractor and frontal loader	Diesel	1,71	0,07	0,221	2,01	19%
	Lubricant		0,02			
Tractor and chipper	Diesel	4,44	0,18	0,361	5,01	48%
	Lubricant		0,04			
Tractor and trailer	Diesel	2,05	0,08	0,59345	2,74	26%
	Lubricant		0,02			
		84%	16%		10,48	

Table 15: Kg Co2 eq. /MWh emissions resulted in Vb operation by mechanized harvesting system.

		Direct emission	Indirect emission		Total emission	
			Fuel production	Machine production		
Harvester	Diesel	12,25	0,49	0,516	13,30	78%
	Lubricant		0,05			
Tractor and trailer (2)	Diesel	2,72	0,11	0,857	3,71	22%
	Lubricant		0,02			
		88%	12%		17,01	

( )Number

CONCLUSIONS AND PERSPECTIVES

The studies carried out in Italian forest yards provided models for harvestable biomass calculations, using the whole tree system, comparing the new system to traditional harvesting, in stands where trees diameter remained under 20 cm. In coppice stands, traditionally harvested for firewood production, was calculated a 30% residual biomass. A similar value was recorded in pine thinning, comparing whole tree to stem harvesting, in this case was possible to obtain an information about needles component, resulted 2% of whole tree mass, so it could be preferable to leave foliage in the stand, during harvesting operations, in order to maintain site fertility. Thought the study of SRF plantations on marginal agricultural lands were assessed plantations yields for different species and conditions. A field seasoning of whole trees showed the possibility to reduce moisture content under Italian winter climate conditions, however in future will be needed a careful analysis about possible dry matter losses and heating values variations. New technical solutions to reduce material moisture content are needed in pine plantations, so a possible solution could be to leave tree bunches into the stand for a field seasoning period, before extraction, but also in this case additional information about biomass losses are needed. Certainly the seasoning period will promote needles separation from twigs allowing to maintain an important fertility component into the stand soil. The introduction of felling frame in motor-manual felling operation led to a scarce productivity increase in comparison to traditional chainsaw, this device resulted particularly suitable when felling trees with stump diameter inferior to 15 cm and over this diameter productivity benefits disappeared. While ergonomic benefits resulted extremely important especially when the felling operations were carried out by a single operator. In this case, the lower fatigue level reduced delays and allowed to simplify tree directional falling, so improving work quality and reducing possible damages in whole tree extraction. Moreover in post-fire restoration cutting the felling frame showed the possibility to significantly reduce stump heights, so increasing the biomass removal and reducing drawbacks in whole tree extraction.

The results of thinning operations allowed to identify models for traditional chainsaw and felling frame work time calculations in dependence of stump diameters, these models could be used in the calculation of felling productivity in similar work conditions.

A model for felling times calculations by number of stems per stump was obtained in coppice stand, this information is particularly useful in Italy, since large literature was produced about traditional firewood cutting and processing, using the short wood system, but scarce information about small tree felling-bunching operations in coppices is available. In future it will be interesting to identify predictive models based on diameter at stump of single stems to be integrated in the found model.

The comparison carried out in SRF plantations confirmed the superiority of the cleaning saw in comparison to chainsaw with felling frame, the study results suggested the use of this machine when stump diameter is 5 cm, especially in cleaning operations. While further investigations are needed to point out cutting performance differences in case of numerous stem per stump, since the chainsaw bar could allow to cut more trees in a single movement. In these plantation the introduction of mechanization increase operation productivity reducing chips costs, however harvester heads must be further improved to ensure adequate productivity.

Analysis of small trees extraction in different conditions demonstrated that variables mostly affecting the work productivities were the number of trees per load and extraction distances. Extraction time models allow simulation in similar contexts, and particularly when the whole tree is harvested in a coppice clear cut or in thinning operations. A possible increase of extracted loads could be obtained acting on operators training in felling-bunching and using chocker hooks on winch cables, so allowing to extract more bunches per time. The study performed in pine thinning clearly showed that increasing winched load by a single tree addiction, the productivity raises 20%. The study results in small trees extraction showed that the machine pulling forces are underexploited, so it is particularly recommended the use of double drum winches in small tree extraction on slope terrain.

Besides these considerations, for skidding distances superior to 100m will be preferable a wheeled tractor, resulting faster than tracked farm tractors used in Italian forestry operations. Moreover toady are available small sized wheeled tractors, frame steered and with a low center of gravity, so resulting particularly competitive with tracked machines on forest trails.

New technical solutions are needed to simplify cable extension in winching operations, since this time is closely related to operators work capacity, so new solutions could allow a reduction of the crew members and consequently lower operation costs could be achieved.

The comparison of winch and small cable yarder in whole tree extraction pointed out an higher productivity for winch extraction. However the cable yarder resulted particularly suitable in rough terrain conditions, where the capacity to overcome obstacles is particularly evident, reducing delays and leading productivity to the same level of forest winch. However, the incidence of line installation time had too high incidence on operation costs when the material to be harvested per line have not reached values given by literature. The field study indicated the needing of specific operator training in cable yarder use to increase extracted loads, since chokers were fixed on the carriage hook in order to raise productivity but the devices were not adequately used by operators.

The economic analysis of small tree harvesting for energy wood in Italy in different experimental stands showed that economic sustainability actually is not achieved, neither by coppice harvesting nor by silvicultural practices in young stands. An economic sustainability could be achieved in coppice stands, if the whole tree harvesting will be addressed to integrated production of firewood and residues for energy. However, ecological models should be developed to predict the effects due to the whole trees removals in Mediterranean conditions, analyzing nutrients losses, and possible effects on slope stability. In SRC plantation resulted difficult to achieve an economic profitability selling chips as energy wood, suggesting small scale mechanization in case of low yields and a completely mechanized system for higher plantation yields. A significant cost reduction could be possible improving harvester heads actually used in mechanized operations.

Analysis of environmental sustainability pointed out low levels of $C0_2$ eq. emissions in all small scale yards, where the whole tree harvesting system was used. The emission balance showed that these emissions are mainly related to whole tree extraction (80% of total emissions), since this phase required machines with an high fossil fuels consumption. The balance underlined that the fuels consumption had the greatest influence on emissions, while CO_2 linked to machinery and fuel production had only a minor effect. These considerations address future choices into machines with high fuel efficiency in order to minimize the total emissions in energy wood harvesting. Thus, a small scale mechanization could result particularly preferred, since in energy wood harvesting the environmental sustainability is fundamental. An other strategy to reduce fuel consumption pass through an higher work productivity, since a shorter time spent in harvesting operation will save fuel consumption per unit of product. Analyzing emission in SRC harvesting for energy chips resulted particularly evident the role of comminution in the emission balance, since the high power request. Emission balance showed that complete mechanization with a medium power request result more environmental sustainable than high power output machines, since increasing machine power was not obtained a proportional productivity increase, so considerably affecting supply chain emission balance.

The study of Swedish reality, trough thinning of young birch stands with stem sizes of 40 dm^3, showed that the quantity of obtainable energy wood doubled the pulpwood removal. The simulation in different stand fertility showed that the volume of pulpwood exceed 30 m^3/ha, considered nowadays the threshold for profitable harvesting, only the best site conditions and with intense thinning removal. As a consequence the gross income for pulpwood resulted in average 33% of energy wood. Energy wood harvesting productivities resulted three times those reached in pulpwood harvesting. Therefore, net incomes were positive in all energy wood harvesting conditions, while pulpwood treatment did not reached economic sustainability. The study addressed the treatment, in current market conditions, towards the use of thinning removal for energy wood production. However a further knowledge will be needed about ecological effects of whole tree removal, considering nutrients removal and soil compaction. New feller heads, still in prototype phase, may offer compromise solutions, releasing during bunching operations the smaller tree components like needles and twigs, so this partial defoliation could allow to maintain site fertility.

It would be interesting a future comparison of machines widely used in small and large scale energy wood harvesting with "Combi" machines, actually known in Sweden, based on a small forwarder (18 kW) with a load capacity of 3 tonnes, allowing the whole trees cutting bunching and the contextual forwarding. These machines can be fitted with small winches, allowing to extract trees from distances greater than 10 m. These small machines could result particularly suitable in first thinning of Italian pine forest, so reducing the cost gap between small and large scale energy wood harvesting. At the same time future research must approach more geometric thinning patterns through tree corridors removal, allowing a better accessibility, so increasing machines productivity and enhancing economic sustainability.

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