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COPPICE FORESTS HARVESTING MECHANIZATION: MULTIDISCIPLINARY APPROACHES APPLIED ON CASE STUDIES

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Foreword

The entire work conducted during three years of studies, aimed at increase knowledge about forest operations, is gathered in this manuscript. Starting from the key role of coppice and from the necessity of mechanize forest operations, three studies were developed including production, economic and environmental aspects. The structure of this thesis is referred to the modern style generally used worldwide for PhD thesis. In detail, the Introduction at the beginning of the manuscript contains the background and the aims of the whole work, while specific arguments are reported as in articles, one for each chapter, with an independent structure. The three papers that compose the PhD thesis are focused on felling, processing and extraction operation respectively. Each chapter is about to be or has been published as a research article in international indexed peer-reviewed journals. A resume of the most important results and some reflection about further developments are reported into the conclusion section. The paper references are reported below:

- *Mortality, re-sprouting vigor and physiology of coppice stumps after mechanized cutting*; Spinelli R, Pari L, Aminti G, Magagnotti N, Giovannelli A; Annals of forest science 74-2017, pp. 1-12.

- *A low-investment technology for the simplified processing of energy wood from coppice forests;* Spinelli R, Lombardini C, Marchi E, Aminti G; submitted to European Journal of Forest Research.

- *The effect of harvesting method on biomass retention and operational efficiency in low-value mountain forests*; Spinelli R, Magagnotti N, Aminti G, De Francesco F, Lombardini C; European journal of forest research 135-2016, pp. 755-764.

CHAPTER 1 - Introduction

European forestry was characterized by human activity due to the long and intense settlement history (Szabó, 2009). Most forests have been under active management until recent years (Kirby & Watkins, 1998). A common method of woodland management is coppicing, such stands are well suited to satisfy the immediate material needs of a dense rural population (Wolfslehner, Krajter, Jovic, Nestorovski, & Velichkov, 2009). Applying the vegetative regeneration capabilities of woody species for managing forests has a long tradition and is still widespread worldwide (Bruckman, Terada, Fukuda, Yamamoto, & Hochbichler, 2016; Marchi et al., 2016). Analysis of oak tree rings revealed that coppicing must have been a sylvicultural practice since the late Roman period in entire Western Europe (Haneca, Van Acker, & Beeckman, 2005). For centuries, these forests have provided local communities with firewood, posts, tool handles, fencing materials (Buckley, 1992), and have also represented an important source of litter collection and pasture (Gimmi, Bürgi, & Stuber, 2008; Glatzel, 1999). Moreover coppice stands are frequently economically efficient due to the short waiting time (15-30 years of rotation period) and simplified management (Spinelli, Cacot, et al., 2016).

This woodland were affected by a progressive abandonment during the last 150 years as a consequence of environmental policies and socio-economic changes (Bicik & Jelecek, 2009; Bürgi, 1999; Lo Monaco et al., 2014; Picchio, Maesano, Savelli, & Marchi, 2009). The result is the current presence of many low-quality hardwood stands originating from coppice forests, after management was discontinuous for many years (Schweier, Spinelli, Magagnotti, & Becker, 2015). Some factors that caused this process were the rural migration to the cities, the introduction of fossil fuels (Hédl, Kopecký, & Komárek, 2010; Laina, Tolosana, & Ambrosio, 2013) and the reduced availability of rural labour, willing to accept heavy and low-paying jobs (Magagnotti, Pari, & Spinelli, 2012; Spinelli, Cacot, et al., 2016). Furthermore, another trend that distinguish this period was the conversion of coppice to high forests (Pyttel, Köhn, & Bauhus, 2015), especially in central and north-western Europe (Matthews, 1991; Peterken, 1993). Such modification of forest management aimed to produce large and more valuable trees (Matula et al., 2012; Wolfslehner et al., 2009), and was encouraged by the demand for higher-quality timber (Hédl et al., 2010).

Coppice stands gained renewed attention during the past two decades because of multiple reasons (Schweier et al., 2015). On one hand the increasing demand for energy wood in Europe: a rapid increment in wood demand is expected, increasing by 10 to 300 millions of m^3 in the period 2010-2030 (Sikkema & Fiorese, 2014). This trend is mainly due to the new policies about renewable energies: the new Renewable Energy Directive (RED) 2009/28/EC assigned to Europe the objective of reaching the 20% of energy production from renewable resources by 2020 and the 42% of this quote is expected to derive from woody biomasses (EU, 2009). Another reason for the growing interest in coppicing is the multidisciplinary approach to woodland administration. With rising living standards, the protective, environmental, social and cultural functions of forests became more important (Spiecker, 2003). Several times coppicing has been suggested as a valuable management practice for nature conservation and for wildlife environmental conditions improvement (Espelta, Riba, & Retana, 1995; Franklin & Forman, 1987; Jansen & Kuiper, 2004; Johnson & Krinard, 1983). Coppice harvesting is a vital operation in forest management (Marchi et al., 2016), which has important effects on the understory, fauna and soil (Frey, Niklaus, Kremer, Lüscher, & Zimmermann, 2011; Picchio, Magagnotti, Sirna, & Spinelli, 2012).

The importance of coppice management is also highlighted in by the EU projects focused on this topic during last years (e.g. the European networking project CForSEE, "Coppice for SE Europe, the multi-functional management of coppiceforests" (2007–2013); COST Action FP1301-EuroCoppice, "Innovative management and multifunctional utilization of traditional coppice forests, an answer to future ecological, economic and social challenges in the European forestry sector"; Life project FutureForCoppiceS, "Shaping future forestry for sustainable coppices in southern Europe: the legacy of past management trials").

Actually, in Europe, coppice is especially common in France (6.4 million ha), Spain (4 million ha), Italy (3.3 million ha), Bulgaria (1.9 million ha), Serbia (1.5 million ha), Bosnia-Herzegovina (1.3 million ha). Portugal, Croatia, Macedonia, and Hungary represent between 0.5 and 1 million hectares of coppice each. Such stands account for much smaller areas in the other European countries, but are present in all of them, at least to some extent (Nicolescu et al., 2017).

This wood supply is often left in the forest due to non technical (e.g. missing forest owners' motivation) and technical barriers such as lack of efficient mechanization (Ferranti, 2014).

In the last decade, mechanization level of forest operations increased quickly to enhance their productivity and to reduce production cost. Harvesters, processors, and forwarders, initially developed and studied in Nordic countries, became widespread among all industrialized countries, (Brunberg, 1997; Nurminen, Korpunen, & Uusitalo, 2006). Today, the use of these machines is no longer limited to gentle terrain (e.g., slope gradient < 25%) and conifer forests, as demonstrated by their massive deployment in the Austrian (Stampfer, 1999) and Swiss (Frutig, Fahmi, Settler, & Egger, 2007) mountain forests, or in the French (Cuchet & Morel, 2001; Martin, Lapeyre, Douchet, Restoy, & Guegand, 1996) and German (Schorr, 2000) hardwood stands. Harvesters and forwarders are also very popular in Mediterranean countries, such as Spain, Portugal (Spinelli, Owende, Ward, Tornero, & Comparison, 2004), and Italy (Cielo & Zanuttini, 2004), where they perform much of the harvesting in the industrial pine, eucalypt, and poplar plantations.
Nevertheless, moving to natural hardwood stands this situation changes radically, especially concerning oak and beech formations, that represent much of the Mediterranean countries forest cover (Ciancio & Nocentini, 2004). In these areas the introduction of mechanized harvesting is progressing slower than expected. This might be related to several factors, for instance the socio-economic conditions of Mediterranean mountains, characterized by small enterprises with low investment capacity. Steep terrain and small stem size represent severe constrains, which are encountered in most coppice stands (Magagnotti et al., 2012). Another limit to forest mechanization is the low density of forest road network. Many stakeholders connected to coppice forests fear that the larger size and weight of new machines may result in a significant increase of stand and soil impacts (Vokoun, Amacher, & Wear, 2006). However, traffic with high axle loads and high contact pressures provoke tremendous soil stresses. If internal soil strength is exceeded, this cause soil compaction, deformation, displacement and therefore partial soil profile disturbance and damages (Klaes, Struck, Schneider, & Sch??ler, 2016). These effects are followed by changes of the mechanical, physical, chemical and biological properties of forest soil with negative impact (Ampoorter, Goris, Cornelis, & Verheyen, 2007; Cambi, Certini, Neri, & Marchi, 2015; Horn, Vossbrink, & Becker, 2004; Keller et al., 2013). A further constraint connected to coppice harvesting mechanization is the need to prevent stump and standard damages in order to guarantee prompt regeneration. The peculiarity presence of multiple stems on the same stump, as well

as shoot irregular shape (e.g. basal band, strong branches and narrow insertion angle), makes mechanized felling and processing especially challenging. Such stem crowding hinders felling head movements and can be handled by very compact units only (Spinelli, Cacot, et al., 2016).

Commonly, coppice sprouts are felled and processed motor-manually and extracted with cable skidders, tractors with forwarding bins or forwarders, depending on log size and slope gradient (Bigot & Cuchet, 2003). The whole tree harvesting (WTH) is also used, but less frequently. Low productivity and high labour inputs of traditional motor-manual operations result in high harvesting costs, which may reduce the financial sustainability of coppice forest management. However, the most critical problem is the high risk associated with manual felling, which is the operation connected with the majority of the fatal accidents (Albizu-Urionabarrenetxea, Tolosana-Esteban, & Roman-Jordan, 2013). Replacing manual felling with mechanized felling may significantly reduce the accident rates (Bell, 2002).

For all this reasons, improve the efficiency of coppice harvesting operations is crucial, since it can contribute to support rural development, while providing a wide range of new product and services, especially soil protection, biodiversity, energy biomass and carbon sequestration (Vacik, Zlatanov, Trajkov, & Dekanic, 2009).

The aim of this thesis was to analyse some of the most important and actual research topics related to coppice harvesting mechanization. In particular, three main phases of forest operations were deeply investigated in order to study the production and the financial performances of innovative machines together with other environmental and silvicultural aspects. As largely explained in this section, several interests from different stakeholders characterize forest sector. Moreover forest operations are connected to a wide range of social, environmental and economical aspects. For this reasons a multidisciplinary approach is needed, and a deep collaboration between researchers from different field is desirable. Felling, processing and extraction operations were investigated in this thesis by analysing representative case studies. The goal of each study was to provide innovative approach and original results and knowledge about coppice harvesting mechanization.

1.1. REFERENCES

Albizu-Urionabarrenetxea PM, Tolosana-Esteban E, Roman-Jordan E (2013) Safety and health in forest harvesting operations. Diagnosis and preventive actions. A review. For Syst 22:392–400. doi: 10.5424/fs/2013223-02714

Ampoorter E, Goris R, Cornelis WM, Verheyen K (2007) Impact of mechanized logging on compaction status of sandy forest soils. For Ecol Manage 241:162–174. doi: 10.1016/j.foreco.2007.01.019

Bell JL (2002) Changes in logging injury rates associated with use of feller-bunchers in West Virginia. J Safety Res 33:463–471. doi: 10.1016/S0022-4375(02)00048-8

Bicik I, Jelecek L (2009) Land use and landscape changes in Czechia during the period of transition 1990-2007. Geografie 114:263–281.

Bigot M, Cuchet E (2003) Mechanized harvesting system for hardwoods. In: 2nd Forest Engineering Conference. Växjö, Sweden, pp 1–10

Bruckman VJ, Terada T, Fukuda K, Yamamoto H, Hochbichler E (2016) Overmature periurban Quercus–Carpinus coppice forests in Austria and Japan: a comparison of carbon stocks, stand characteristics and conversion to high forest. Eur J For Res 135:857–869. doi: 10.1007/s10342-016-0979-2

Brunberg T (1997) Basic data for productivity norms for single-grip harvesters in thinning. Skogsforsk Redogörelse n. 8. Uppsala, Sweden

Buckley GP (1992) Ecology and management of coppice woodlands. Chapman & Hall, London

Bürgi M (1999) A case study of forest change in the Swiss lowlands. Landsc Ecol 14:567–575. doi: 10.1023/A:1008168209725

Cambi M, Certini G, Neri F, Marchi E (2015) The impact of heavy traffic on forest soils: A review. For Ecol Manage 338:124–138. doi: 10.1016/j.foreco.2014.11.022

Ciancio O, Nocentini S (2004) Il bosco ceduo (Coppice forests). Selvicoltura, Assestamento, Gestione. Accademia Italiana di Scienze Forestali, Florence

Cielo P, Zanuttini R (2004) La raccolta del legno nei pioppeti (Wood harvesting in poplar plantations). l'Italia For e Mont 6:467–482.

Cuchet E, Morel P (2001) Evolution du bucheronnage mechanisé, cas de la Bourgogne et perspectives nationales (Evolution of mechanized processing, the case of Burgundy). Infomation For 631:6 pp. (in French).

Espelta JM, Riba M, Retana J (1995) Patterns of seedling recruitment in West-Mediterranean Quercus ilex forests influenced by Canopy development. J Veg Sci 6:465–472. doi: 10.2307/3236344

EU (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy From Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC.

Ferranti F (2014) Energy wood: A challenge for European forests. Potentials, environmental implications, policy integration and related conflicts Francesca Ferranti. EFI Tech Rep 95, 2014 158.

Franklin JF, Forman RTT (1987) Creating landscape patterns by cutting: biological consequences and principles. Landsc Ecol 1:5–18.

Frey B, Niklaus PA, Kremer J, Lüscher P, Zimmermann S (2011) Heavy-machinery traffic impacts methane emissions as well as methanogen abundance and community structure in oxic forest soils. Appl Environ Microbiol 77:6060–6068. doi: 10.1128/AEM.05206-11

Frutig F, Fahmi F, Settler A, Egger A (2007) Mechanisierte Holzernte in Hanglagen (Mechanized harvesting in steep terrain). Wald und Holz 7:47–52.

Gimmi U, Bürgi M, Stuber M (2008) Reconstructing anthropogenic disturbance regimes in forest ecosystems: A case study from the Swiss Rhone valley. Ecosystems 11:113–124. doi: 10.1007/s10021-007-9111-2

Glatzel G (1999) Causes and consequences of accelerated tree growth in europe. In: EFI proceedings. pp 65–74

Haneca K, Van Acker J, Beeckman H (2005) Growth trends reveal the forest structure during Roman and Medieval times in Western Europe: a comparison between archaeological and actual oak ring series (Quercus robur and Quercus petraea). Ann For Sci 62:797–805. doi: 10.1051

Hédl R, Kopecký M, Komárek J (2010) Half a century of succession in a temperate oakwood: From species-rich community to mesic forest. Divers Distrib 16:267–276. doi: 10.1111/j.1472-4642.2010.00637.x

Horn R, Vossbrink J, Becker S (2004) Modern forestry vehicles and their impacts on soil physical properties. Soil Tillage Res 79:207–219. doi: 10.1016/j.still.2004.07.009

Jansen P, Kuiper L (2004) Double green energy from traditional coppice stands in the Netherlands. Biomass and Bioenergy 26:401–402. doi: 10.1016/j.biombioe.2003.08.004

Johnson RL, Krinard RM (1983) Regeneration in small and large sawtimber sweetgum-red oak stands following selection and seed tree harvest. South J Appl For 7:176–184.

Keller T, Lamandé M, Peth S, Peth S, Berli M, Delenne J-Y, Baumgarten W, Rabbel W, Radjai F, Rajchenbach J, Selvadurai A.P.S., Or D (2013) An interdisciplinary approach towards improved understanding of soil deformation during compaction. Soil Tillage Res 128:61–80. doi: 10.1016/j.still.2012.10.004

Kirby K, Watkins C (1998) The ecological history of European forests, 1st edn. CAB International

Klaes B, Struck J, Schneider R, Schüler G (2016) Middle-term effects after timber harvesting with heavy machinery on a fine-textured forest soil. Eur J For Res 135:1083–1095. doi: 10.1007/s10342-016-0995-2

Laina R, Tolosana E, Ambrosio Y (2013) Productivity and cost of biomass harvesting for energy production in coppice natural stands of Quercus pyrenaica Willd. in central Spain. Biomass and Bioenergy 56:221–229. doi: 10.1016/j.biombioe.2013.04.016

Lo Monaco A, Calienno L, Pelosi C, Balletti F, Agresti G, Picchio R (2014) Technical properties of beech wood from aged coppices in central Italy. IForest 8:82–88. doi: 10.3832/ifor1136-007

Magagnotti N, Pari L, Spinelli R (2012) Re-engineering firewood extraction in traditional

Mediterranean coppice stands. Ecol Eng 38:45–50. doi: 10.1016/j.ecoleng.2011.10.006

Marchi E, Picchio R, Mederski PS, Vusic D, Peruguni M, Venenzi R, (2016) Impact of silvicultural treatment and forest operation on soil and regeneration in Mediterranean Turkey oak (Quercus cerris L.) coppice with standards. Ecol Eng 95:475–484. doi: 10.1016/j.ecoleng.2016.06.084

Martin P, Lapeyre D, Douchet O, Restoy G, Guegand G (1996) Récolte mécanisée des taillis en bois ronds (Mechanized harvesting of roundwood from coppice forests). AFOCEL Fiche Information- Forêt 540:6 pp. (in French).

Matthews JD (1991) Silvicultural Systems. Claredon Press, 1991, Oxford

Matula R, Svátek M, Kůrová J, et al (2012) The sprouting ability of the main tree species in Central European coppices: Implications for coppice restoration. Eur J For Res 131:1501–1511. doi: 10.1007/s10342-012-0618-5

Nicolescu V, Bartlett D, Buckley P, Rossney D, Pyttel P, Unrau A (2017) National Perspectives on Coppice from 35 EuroCoppice Member Countries. COST Action FP1301 Reports, Freiburg, Germany

Nurminen T, Korpunen H, Uusitalo J (2006) Time Consumption Analysis of the Mechanized Cut-to-length Harvesting System. Silva Fenn 40:335–363.

Peterken GF (1993) Woodland Conservation and Management. Springer Science & Business Media, London

Picchio R, Maesano M, Savelli S, Marchi E (2009) Productivity and Energy Balance in Conversion of a Quercus Cerris L. Coppice Stand into High Forest in Central Italy. Croat J For Eng 30:15–26.

Picchio R, Magagnotti N, Sirna A, Spinelli R (2012) Improved winching technique to reduce logging damage. Ecol Eng 47:83–86. doi: 10.1016/j.ecoleng.2012.06.037

Pyttel PL, Köhn M, Bauhus J (2015) Effects of different harvesting intensities on the macro nutrient pools in aged oak coppice forests. For Ecol Manage 349:94–105. doi: 10.1016/j.foreco.2015.03.037

Schorr M (2000) Der Einfluss von Starkasten und Zwieseln auf die Leistung von Harvestern bei der Laubschwachholzernte Kurzfassung (The influence of branching and stemform on the productivity of harvesters used in hardwood stands). Forst und Holz 16:520–522.

Schweier J, Spinelli R, Magagnotti N, Becker G (2015) Mechanized coppice harvesting with new small-scale feller-bunchers: Results from harvesting trials with newly manufactured felling heads in Italy. Biomass and Bioenergy 72:85–94. doi: 10.1016/j.biombioe.2014.11.013

Sikkema R, Fiorese G (2014) Use of forest based biomass for bioenergy in EU-28. Res Rural Dev 2:7–13.

Spiecker H (2003) Silvicultural management in maintaining biodiversity and resistance of forests in Europe-temperate zone. J Environ Manage 67:55–65. doi: 10.1016/S0301-4797(02)00187-1

Spinelli R, Cacot E, Mihelic M, Nestorovski L, Mederski P (2016) Techniques and productivity of coppice harvesting operations in Europe: a meta-analysis of available data. Ann For Sci 73:1125–1139. doi: 10.1007/s13595-016-0578-x

Spinelli R, Owende PMO, Ward SM, et al (2004) Comparison of Short-Wood Forwarding Systems Used in Iberia. Silva Fenn 38:85–94.

Stampfer K (1999) Influence of terrain conditions andthinning regimes on the productivity of a track-based steep-slope harvester. In: International Mountain Logging and 10th Pacific Northwest Skyline Symp. Corvallis, Oregon,

Szabó P (2009) Open woodland in Europe in the Mesolithic and in the Middle Ages: Can there be a connection? For Ecol Manage 257:2327–2330. doi: 10.1016/j.foreco.2009.03.035

Vacik H, Zlatanov T, Trajkov P, Dekanic S (2009) Role of coppice forests in maintaining forest biodiversity. Silva Balc 10:35–45.

Vokoun M, Amacher GS, Wear DN (2006) Scale of harvesting by non-industrial private forest. J For Econ 11:223–244. doi: 10.1016/j.jfe.2005.10.002

Wolfslehner B, Krajter S, Jovic D, Nestorovski L, Velichkov I (2009) Framing stakeholder and policy issues for coppice forestry in selected central and south-eastern European countries. Silva Balc 10:21–34.

CHAPTER 2 – Mortality, re-sprouting vigor and physiology of coppice stumps after mechanized cutting

2.1. ABSTRACT

Coppice harvesting must be mechanized in order to modernize coppice management, so that it can grow along with the dynamic new bio-economy. However, foresters are concerned that mechanized cutting may result in a higher stump damage levels, which may cause increased mortality and lower growth rates.

The goal of the study was to compare manual and mechanized cutting in terms of cut quality, stump damage levels, stump mortality, re-sprouting vigour and shoot growth. The study was conducted in a classic Mediterranean coppice stand located in central Italy. The oak-dominated coppice was cut using a chainsaw (control), a disc saw and a shear. The experiment adopted a split-plot design, based on 5 plots divided into 15 subplots (one subplot per plot and technology). Overall, 344 stumps were selected, tagged and monitored over the first growing season after cutting. Stump size, cutting height and cutting damage were determined right after cutting. At the end of the first growing season the following parameters were also recorded: n° of shoots; height, diameter and type of the tallest 5 shoots. Samples were collected from randomly selected stumps during the main phenologic phases in order to determine the content of C, N, starch and soluble sugar, as well as the C/N ratio.

Mortality was limited and ranged from 4 to 8%. Re-sprouting was generally vigorous, and dominant shoots often exceeded the height of 1.5 m after one year. Cutting technology had a significant effect on cutting height and cutting damage, but it had no effect on mortality, re-sprouting vigor and nutrient balance within the stumps, at least in the first growing season. In contrast, regeneration vigor was found to depend mainly on species.

While it may result in higher stump damage levels, mechanized cutting does not seem to have any effects on coppice regeneration and growth, at least in the first year. Previous studies indicate that effects recorded during the first growing seasons may be representative of longer-term trends, but the experiment will be further continued to obtain additional confirmation.

2.2. INTRODUCTION

Coppice forests represent an extreme example in the domestication of woodlands. Coppice management offers the benefits of short waiting time and simplified care, which make it very efficient in providing rural communities with firewood, posts, tool handles and fencing materials (Buckley 1992). For this reason, coppice forests were widespread all over Europe until recent times, when industrialization transformed both the economy and the landscape of many Regions (Coppini and Hermanin 2007). Nevertheless, Coppice stands have survived in rural areas, because they are best suited to provide for the immediate material needs of a dense rural population (Wolfslehner et al. 2009). Today, coppice is still abundant in the Mediterranean and the Balkan regions (Jansen and Kuiper 2004), but it suffers from the competition of oil and plastic, which results in a reduced interest towards active coppice management (Hédl et al. 2010).

The rapidly expanding biomass economy represents an ideal opportunity for reviving coppice management (Matula et al. 2012). Biomass users need large amounts of low-quality wood at short intervals, which is what coppice was designed to produce in the first place. While new short-rotation coppice stands are being established on ex-arable land, existing coppice forests might represent an even larger source of raw material for the growing bio-economy, and could be returned to active and profitable management. In fact, the increasing demand for food products has weakened both the financial and the ethical sustainability of short-rotation coppice (Glithero et al. 2013), leaving conventional coppice forests as a more desirable solution for matching the large feedstock demands of the modern bio-economy (Ollikainen 2014).

Here the attribute “modern” is key: an old production system can hardly satisfy the requirements of a modern user. Coppice forests can enjoy the benefits of the modern bio-economy only if coppice management is modernized. For this reason, it is important to facilitate the transition of coppice management from a part-time rural activity to a modern industrial business. Mechanization may seem the obvious solution, because it compensates for the reduced availability of rural labor, with inadequate propensity to perform heavy and low-paying jobs. Much progress has already been made, with the massive introduction of modern forwarders and tower yarders in coppice harvesting operations (Spinelli et al. 2016). However, tree felling is still performed motor-manually in most cases (Spinelli et al. 2014a).

The presence of multiple stems on the same stump offers a serious challenge to the introduction of mechanized felling to coppice harvesting operations, because stem crowding hinders felling head movements, and can be handled by very compact units only (Suchomel et al. 2012). However, many studies have already shown that coppice felling can be mechanized if the right technology is applied with sufficient skill (McEwan et al. 2016). In that respect, the last hurdle is represented by the absolute need to prevent stump damage, in order to guarantee prompt regeneration. All cuts must be clean and as near to the ground as possible. Since mechanical felling cannot guarantee that these requirements are met, forest managers often forbid mechanized felling in their coppice forests and accept the higher cost of motor-manual felling.

Unfortunately, financial viability is not the only issue at stake, and not the main one either. Manual felling is associated with the highest accident risk and accident severity, and it accounts for most of the fatal accidents recorded in forest operations (Albizu et al. 2013). Previous studies have shown that the introduction of mechanized felling may reduce accident rates by a factor 4 (Bell 2002), and therefore replacing manual felling with mechanized felling is a strategic ethical requirement,.

Such crucial issue must be solved, if coppice management has to be rescued from its slow decline. For this reason, a compromise must be found between ideal practice and the operational limits of mechanization. In fact, very few scientific papers offer reliable information about the effects of cut quality on stump mortality and re-sprouting vigor. Not only we cannot quantify the losses derived from mechanized cutting, but we cannot even state that losses actually occur in the first place, and neither can we determine the physiological mechanisms involved.

Re-sprouting vigor is strictly related to the carbon and nitrogen reserves of the stump at the time of cutting (Kays and Canham, 1991). After wounding (i.e. cutting) occurs, the emission of new stems requires the mobilization of carbon reserves in the stump – and mainly the starch and the soluble sugars contained inside the parenchymatic rays of roots and stem. In contrast, N mobilization is seasonally programmed and less involved in the response of the plant to perturbations (Milard and Grelet, 2010).

Previous studies have shown a positive relationship between carbon reserves and the mass of sprouts (Schier and Zasada 1973), leading to the formulation of the carbon allocation hierarchy hypothesis. Such hypothesis postulates that re-sprouting vigor is related to the availability of sufficient carbon reserves (Waring and Pitman, 1985), which might be affected by the quality of cutting.

Therefore, the goals of this study were: 1) to determine if mechanized cutting may affect the mortality and re-sprouting of coppiced stumps, 2) to gauge the magnitude of such effects, if present, 3) to analyze the effect of mechanized cutting on the carbon and nitrogen reserves of the stumps, in order to obtain an insight of long-term effects.

2.3. MATERIALS AND METHODS

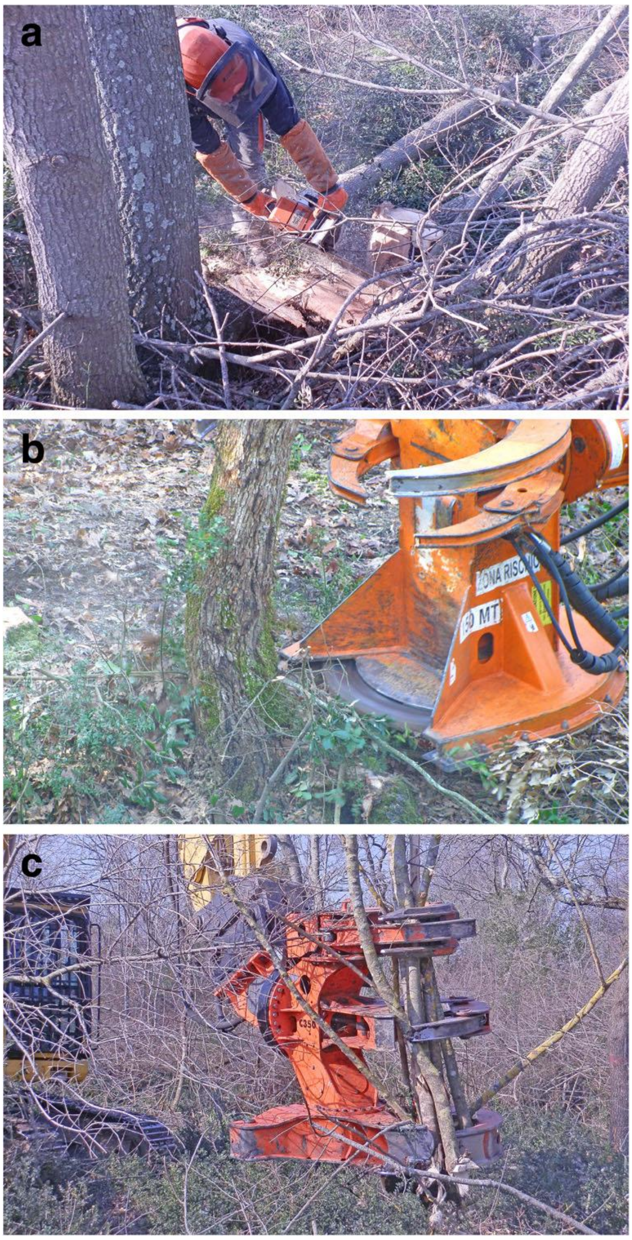
The study was conducted in Italy, where coppice accounts for about half of the total forest surface. With over 3 million hectares, Italy has one of the largest surface of coppice forests in Europe, and it has a strategic interest in harnessing its large coppice resource to the development of a thriving bio-energy sector. The study was performed in a typical oak-dominated coppice stand located at Roccaccia, near the historical town of Tarquinia in Central Italy (42° 34’ 46’’ N, 11° 75’ 29’’ E). Main species were turkey oak (*Quercus cerris* L.), downy oak (*Quercus pubescens* L.), common maple (*Acer campestris* L.), narrow-leaf ash (*Fraxinus angustifolia* Vahl) and manna ash (*Fraxinus ornus* L.), which represented 36%, 7%, 24%, 16% and 4% of the stump numbers, respectively. The remaining 13% of the stumps were mock privet (*Phyllirea angustifolia* L.) and cornelian cherry (*Cornus mas* L.). Oaks and maples constituted the dominant plane, whereas ash, mock privet and cornelian cherry were part of a lower dominated plane. The understorey was a typical consociation of black thorn (*Prunus spinosa* L.), butcher’s broom (*Ruscus aculeatus* L.) and bladder senna (*Colutea arborescens* L.). The diameter at breast height (DBH) of coppice stems ranged from 5 to 30 cm, averaging 15 cm. The stand was 20 years old, and was clearcut with a reserve of approximately 100 standards per hectare. All standards left during the previous rotation were removed. The stand was quite dense, and the harvest amounted to over 150 fresh t ha^{-1}. This figure included tops and branches, because whole-tree chipping was applied with the purpose of producing high-quality boiler fuel. Slope gradient averaged 20%, which allowed easy access to ground-based harvesting equipment. In general, stand characteristics were considered representative of Mediterranean coppice stands, common to large parts of Italy, Southern France, Spain and the Balkans, although in myriads of local variations (Amorini et al. 1998).

Five contiguous sample plots were installed inside the compartment just before commercial harvesting. Each plot measured ca. 70 m × 45 m and comprised of three 15-m wide felling swathes, or subplots. Plots were joined side by side, so that the overall sample area was 70 m long and 225 m wide (i.e. 45 m × 5 plots). The experimental design was a typical split-plot, where three felling treatments were distributed randomly among the three subplots constituting each sample plot. In this case, the advantage of restricted randomization was to avoid poor allocation of treatments in the event of a spatial gradient in soil productivity, which is quite common in natural forests. Climate and exposure conditions were equal across all plots and therefore they did not constitute an expected source of variation.

The three treatments on test were: i) motor-manual felling with a chainsaw (control); ii) mechanized felling with a high-speed circular saw (i.e. hot saw); iii) mechanized felling with a hydraulic shear. The chainsaw was a Stihl MS440, powered by a 70 cm^3 two-stroke engine capable of delivering 4 kW. The chainsaw was equipped with a 50 cm bar. The high-speed circular saw was a GD350 model built by the Italian company COMAF and installed on a 17 t tracked excavator. Finally, the hydraulic shear was a single-knife Woodcracker C model, built by the Austrian company Westtech and installed on a 21 t tracked excavator (Figure 2.1). All machines were operated by experienced professionals, who had run them for several years. The skills of study operators were considered representative of the region and were fairly similar between them. All sample plots were harvested on March 10 and 11, 2015, when the trees were still dormant and the ground was dry. The cutting period was selected specifically for removing any cutting season effects on re-sprouting, because coppicing at the end of the dormant season is considered ideal for promoting vigorous regeneration (Ducrey and Turrel 1992).

The individual stump represented the observational unit for this study. After cut, between 13 and 34 stumps were randomly selected within each subplot, depending on local stand density. The total number of sample stumps amounted to 344 units, or 102, 122 and 120 for the chainsaw, the disc saw and the shear treatment, respectively. The goal was to follow up the re-sprouting of at least 100 stumps per treatment, and therefore a larger number of stumps were initially recruited in order to compensate for the eventual mortality.

Fig. 2.1 - The three cutting technologies on test: chainsaw (**a** on top), disk saw (**b** in the center), and shear (**c** at the bottom)



Each stump was attributed a sequential identification number, clearly marked on a highly-visible yellow plastic tag driven deep into the soil right by stump. For each stump, we recorded: characteristics; cut quality; presence and quality of regeneration after the first growing season; biochemical indicators of stress.

Stump characteristics and cut quality were determined immediately after cut, at the time of selecting and marking the stumps. Each stump was characterized for: species; circumference at cut level; minimum and maximum cut height, measured from ground level; presence of cavities in the stump center; cutting damage. The latter was attributed to one of the following classes: clean cut (no damage), pullout (fibers being pulled off the cut stem), crack (any splitting of the stump) and stump pull (fibers being pulled off the cut stump). Marked stumps were inspected again in early February 2016, in order to check for re-sprouting. Stumps without any shoots were classed as dead and were used to estimate mortality rates. When shoots were present, the following parameters were recorded: n° of shoots taller than 30 cm; height of the 5 tallest shoots; diameter of the 5 tallest shoots taken at 30 cm above ground; insertion of the 5 tallest shoots (i.e. basal shoot, adventitious shoot or root sucker); presence of browsing. In order to minimize browsing damage, all tagged stools were treated with deer repellent three times during the first growing season. Full coverage was provided in May (twice) and late September, when shoots were most attractive and/or when other food sources were scarce. Acknowledging that one-year re-sprouting may not offer a comprehensive picture of stress differences between treatments, the study endeavored to determine the C/N ratio and the sugar type present in the stumps during the main phenological stages. The assumption was that a badly mauled stump might still re-sprout vigorously, but at the cost of an excessive depletion of its own reserves and – conversely – that less abundant re-sprouting might be compensated by a smaller depletion of the stump reserves, which may be indicative of a better long-term performance. For this purpose, samples were collected from 71 stumps, as resulting from the random selection of four to five stumps per subplots. Sample selection was random, but preference was given to the dominant species (oaks), which represented 60% of the total. Sample collection was repeated four times, once for each phenology phase, namely: onset of cambium activity right after felling, exponential growth, offset and dormancy. Therefore, the total number of samples amounted to 284. Each sample consisted of a 5 cm long helical core, obtained from drilling the outermost part of the stump with a 6 mm wood drill bit, working perpendicularly to the surface of the ground. The rotation speed of the drill was maintained below 60 rpm in order to avoid heating. Samples were extracted from the conducting area of sapwood and were composed of the most recent three rings. Sample weight ranged from 100 to 250 mg (fresh weight). After collection, samples were placed in plastic tubes and stored inside a cooler, at a temperature of 4° C. The cooler was moved to the laboratory within 6 hours from sample collection, and the tubes were stored at -80°C until analysis. Sample preparation included freeze drying at -50°C for 96 h, and milling with a Retsch ZM 200 centrifugal mill (Emiliani et al. 2011).

Soluble carbohydrates were extracted at room temperature with 5 ml of deionized water (pH 7) added to 40 mg of powder. The homogenate was placed in a 2 ml Polypropylene Spin-X centrifuge tube equipped with 0.22 μm cellulose acetate filter and centrifuged at 10,000 g at 5°C for 10 min (Giovannelli et al. (2011). The surnatant was analysed using a Perkin Elmer binary LC pump 250 equipped with a ISS101 automatic injection system. The column was an 8mm × 300mm Shodex Sugar SC 1011, and was maintained at 80°C using a water column heater module.

Pellets deriving from soluble sugar extraction were used for starch analyses following the procedure proposed by Deslauriers et al. (2014). The starch was solubilized with acetate buffer (pH 5) and digested with an a-amylase solution at 2000 U mL^{-1} and amyloglucosidase at 10 U mL^{-1}. Colour reagent and 75% H_2SO_4 were added to the solution for staining. Starch was assessed using a spectrophotometer at 533 nm.

Total organic C and total N were determined on 20-mg dry wood powder samples by dry combustion with a Carlo Erba NA 1500 CHSN Analyser (D’Acqui et al. 2010). Each analysis was replicated twice and the mean value was used for statistical analysis. Data were analyzed statistically using SAS Statview, Minitab 16 and R for Excel, depending on the analytical technique. As a first step, descriptive statistics were drawn. The distribution of data was inspected visually, before performing specific statistical tests to gauge deviation from normality (Levene’s test). Homoscedasticity was checked using Bartlett’s test. The significance of the differences between mean values for different options was tested through the analysis of variance (ANOVA) or co-variance (ANCOVA), if the parametric assumptions had not been violated. In that case, differences were pinpointed on treatments using Tukey-Kramer and Fisher’s LSD post-hoc tests. In contrast, if the parametric assumptions had been violated, non-parametric techniques were used (Kruskal-Wallis and Mann-Whitney tests). The significance of any differences between distributions was checked using a classic χ^2 test. Linear regression analysis allowed testing the relationship between re-sprouting vigor and selected independent variables, such as stump size, species and treatment. Indicator variables were used to introduce the effect of categorical variables (i.e. species) when exploring the relationship between re-sprouting vigour and stump size (Olsen et al. 1998).

2.4. RESULTS

Field measurement showed that cutting height was significantly larger for the shear, compared with the chainsaw and the disc saw (Table 2.1). The effect of felling technology accounted for 18% of the variation in the cutting height data, and it was highly significant (p-Value <0.0001). Regression analysis found no relationship between cutting height and stump circumference (R^2 <0.1). Stump circumference was even across all treatments, and changed with species only, which accounted for 14% of the variation in the data (p-Value <0.0001). Mean stump circumference was largest for the oaks (236 cm), smallest for the maple (166 cm) and intermediate for the ash (207 cm). That was consistent with the ecology of the different species and with the biplane structure of the stand, dominated by oak trees.

Cut quality was strongly and significantly affected by cutting technology (χ^2 = 320, p-Value <0.0001). Each technology had its own specific quality mark: the chainsaw produced a significantly larger proportion of clean cuts, compared with all other technologies; the disc saw produced a significantly larger proportion of pullouts, i.e. of fiber pulled from the butt of the felled tree (Figure 2.2). In the specific case of the disc saw, pullout consisted mostly of fine fibers, resulting in a "hairy" cut surface. Finally, the shear produced a significantly larger proportion of crack and stump pull, resulting in a more severe damage level than recorded for any of the other technologies.

Nevertheless, mortality after the first year was independent of cutting technology (p-Value = 0.2510), and amounted to 7.8%, 4.4% and 4.8% respectively for the chainsaw, the disc saw and the shear treatment. In fact, a comparison between dead and regenerated stumps failed to detect any significant differences in terms of cutting height and circumference. However, statistical analysis showed that the frequency of stump pull was 5 times higher among the dead stumps, and that this difference accounted for 70% of the chi-square value (χ^2 = 21.802; p-Value <0.0001).

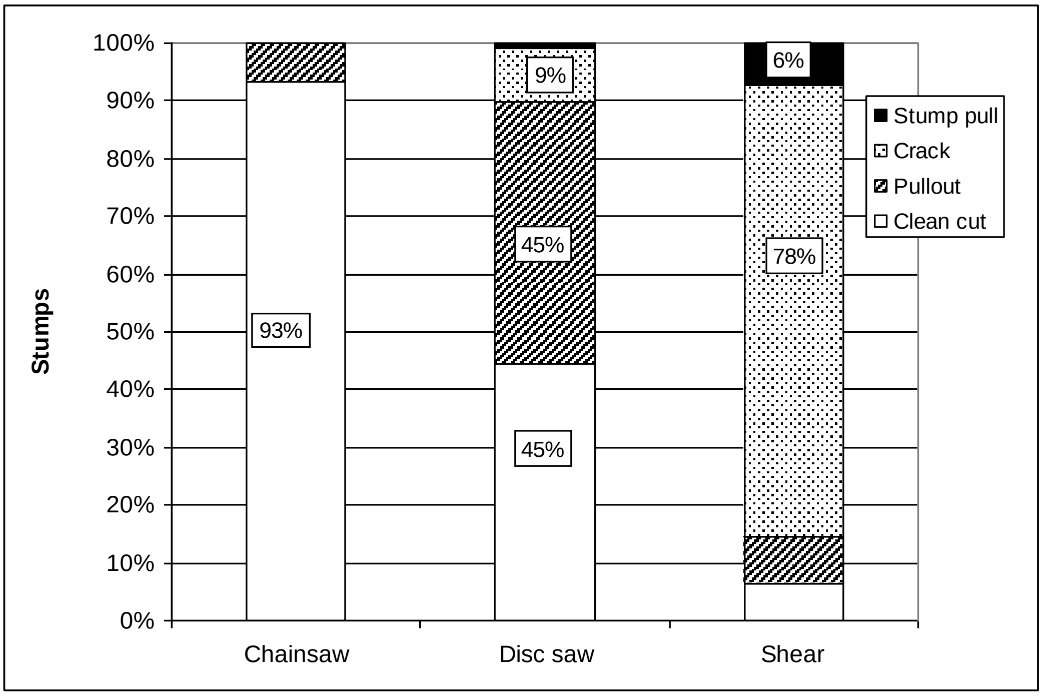
After one year, re-sprouting was measured on a total of 313 stumps, which carried 6481 shoots.

Table 2.1 – Characteristics of the stumps at the time of cut (n = 344)

	Mean	SD	min	max
	Maximum height (cm)			
Chainsaw	9.4^a	3.9	2	27
Disc saw	10.4^a	6.2	0	33
Shear	15.2^b	7.1	3	40
	Minimum height (cm)			
Chainsaw	4.2^a	2.0	0	10
Disc saw	4.9^a	4.3	0	29
Shear	7.8^b	4.6	1	24
	Circumference at cut level (cm)			
Chainsaw	210^a	75	70	410
Disc saw	213^a	88	65	415
Shear	207^a	86	40	460

Notes: SD = standard deviation; different superscript letters for the technology types indicate a statistically significant difference for α<0.05

Fig. 2.2 – Percent attribution of damage class by felling technology type



Diameter, height and insertion type were determined for 1502 dominant shoots instead of 1565 (i.e. 313 stumps × 5 shoots), because 5 shoots were not available on every stump.

The application of repellent was only partially successful, because one stump out of four showed signs of browsing. However, browsing interested less than half of the total number of shoots, and was complete (all shoots interested) on 5% of the stumps, only. Specific preference was evident: while 58% of the ash stumps showed signs of browsing, only 4% of the oak stumps did. Maple was in between, with 35% of the stumps showing signs of browsing.

Re-sprouting vigor was significantly associated with the species and the size of the stumps, as expressed by their circumference (Table 2.2). Maple stumps produced between 1.5 and 2 times more shoots than either oak or ash stumps. However, maple shoots were shorter and had a smaller diameter than oak or ash shoots. Oak stumps produced the largest shoots, for both diameter and height (Table 2.3). Stump size had no effect on the number of shoots produced, but it affected the diameter and the height of dominant shoots. Larger stumps produced taller dominant shoots, with a larger diameter (Figure 2.3). While this was true for all species, diameter and height increments were different for the different species and they were largest for the oaks, and smallest for the maple.

Table 2.2 – Indicators of re-sprouting vigor - ANCOVA

	DF	SS	η^2	F-Value	p-Value
Number of shoots taller than 30 cm - square root transformed					
Treatment	2	12.8	0.02	3.124	0.0455
Species	2	129.7	0.16	31.711	<0.0001
Circumference	1	57.8	0.07	28.26	<0.0001
Residual	291	595.3	0.75		
Mean shoot diameter at 30 cm from the ground (mm)					
Treatment	2	16.8	0.00	0.349	0.7055
Species	2	4620.7	0.37	95.762	<0.0001
Circumference	1	953.9	0.08	39.537	<0.0001
Residual	291	7020.7	0.56		
Mean shoot height (cm) - square root transformed					
Treatment	2	13.3	0.01	1.630	0.1978
Species	2	495.3	0.27	60.473	<0.0001
Interaction	1	144.5	0.08	35.286	<0.0001
Residual	291	1191.6	0.65		

Notes: Diameter and height as measured on the 5 tallest shoots per stump; Circumference measured at cut level; DF = degrees of freedom; SS = sum of squares; η^2= ratio between the SS for the specific effect and the total SS; results for the interaction terms are not reported, because they did not result significant

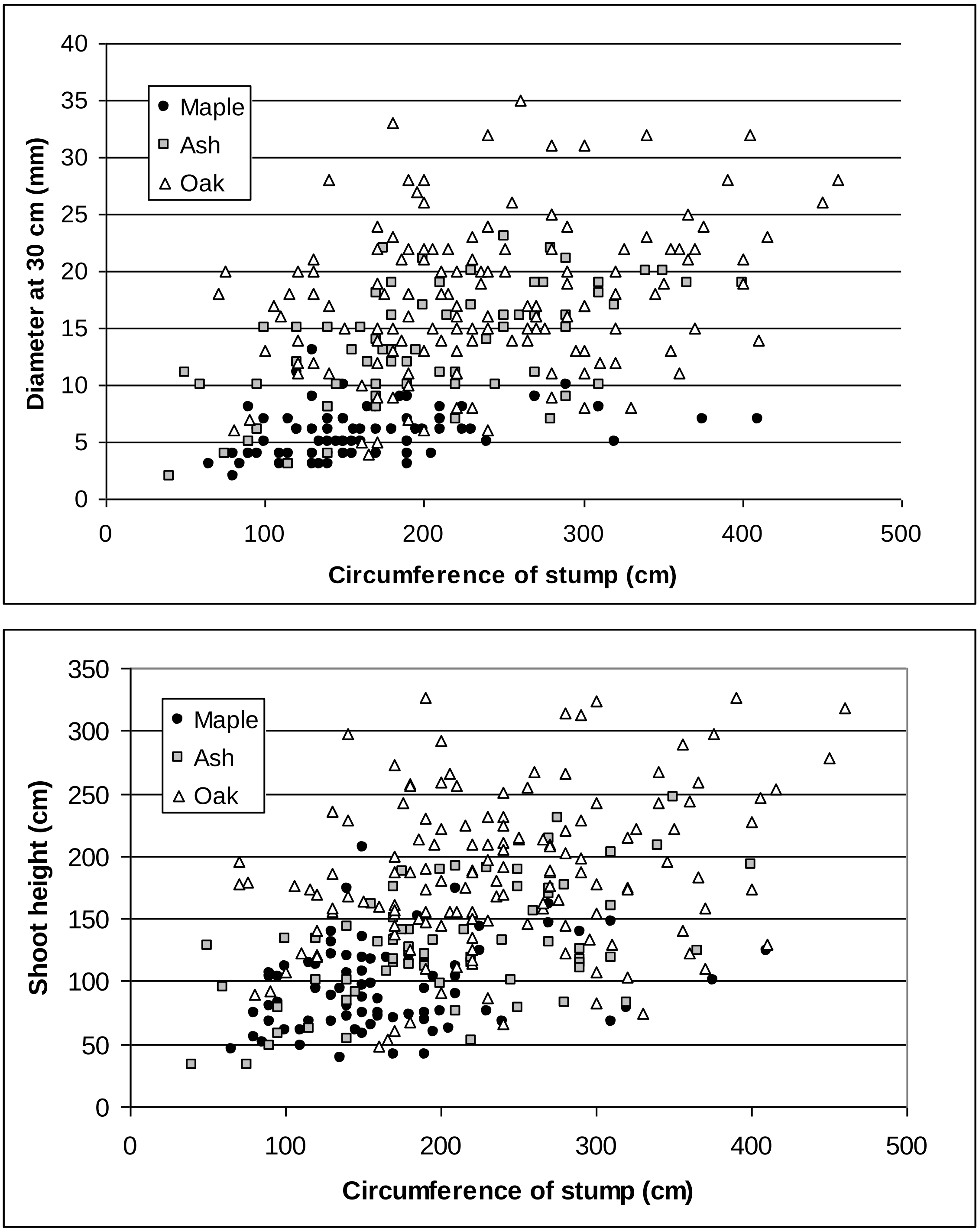
Table 2.3 – Re-sprouting vigor by species and treatment (n = 296)

	Oak		Maple		Ash	
	Mean	SD	Mean	SD	Mean	SD
Number of shoots taller than 30 cm						
Chainsaw	13.7^{a}	7.7	37.5^{a}	19.6	18.0^{ab}	12.6
Disc saw	15.8^{ab}	9.4	23.4^{b}	19.3	13.1^{a}	8.2
Shear	18.7^{b}	10.3	28.6^{ab}	15.8	25.6^{b}	21.3
Mean shoot diameter at 30 cm from the ground (mm)						
Chainsaw	17.6	6.7	6.3	1.9	12.4	5.7
Disc saw	17.3	6.2	5.3	1.9	13.9	4.8
Shear	18.0	6.1	6.1	2.1	14.0	5.5
Mean shoot height (cm)						
Chainsaw	184	63	101	27	114	44
Disc saw	180	59	83	34	136	48
Shear	197	63	100	36	136	46

Notes: diameter and height as measured on the 5 tallest shoots per stump; Oak = consolidated data for Q. cerris L. and Q. pubescens L.; Ash = consolidated data for F. angustifolia Vahl and F. ornus L.; SD = standard deviation; different superscript letters for the technology types indicate a statistically significant difference for $\alpha<0.05$ (reported for number of shoots only, since no significant differences were determined for the other cases)

Regression analysis confirmed that stump size and species effects were both significant, but separate (Table 2.4). Felling technology had no effect on shoot diameter or height, but it had a weak and significant effect on the number of shoots. Cutting with shears resulted in a significant increase in the number of shoots growing on oak stumps, which was 18% and 36% larger than found on oak stumps cut with the disc saw and the chainsaw, respectively. Maple and ash stumps cut with the disc saw presented fewer shoots than maple and ash stumps cut with either the chainsaw or the shear, and the difference varied between 18% and 48%. Felling technology also had an effect on the insertion of dominant shoots. Cutting with the shear reduced by a factor 6 the presence of dominant adventitious shoots on ash stumps, which had a higher propensity for re-sprouting from the callus compared with oak and maple stumps (Table 2.5). A similar effect was also found for oak stumps, although not as strong as for maple stumps. Conversely, cutting with a chainsaw seemed to promote the development of adventitious shoots on all species. Since insertion type was determined for the dominant shoots only, it is impossible to determine if cutting technology affected the emission or the dominance of a certain type of shoots, but the result was unequivocal: the type of dominant shoots was affected by felling technology.

Figure 2.3 – Relationship between stump size and shoot size



Notes: diameter and height as measured on the 5 tallest shoots per stump; Circumference at cut level; Oak = consolidated data for Q. cerris L. and Q. pubescens L.; Ash = consolidated data for F. angustifolia Vahl and F. ornus L.

Table 2.4 – Regression equations for shoot diameter and height

Mean shoot diameter at 30 cm from the ground (mm)

Diameter = a + b Circumference + c Maple + d Oak

R^2 adjusted = 0.531, n = 297

	Coefficient	SE	F-Value	P-Value
a	8.789	0.963	9.131	<0.0001
b	0.023	0.004	6.320	<0.0001
c	-6.727	0.817	-8.231	<0.0001
d	3.326	0.727	4.577	<0.0001

Mean shoot height (cm)

Height = a + b Circumference + c Maple + d Oak

R^2 adjusted = 0.424, n = 297

	Coefficient	SE	F-Value	P-Value
a	84.732	9.655	8.776	<0.0001
b	0.218	0.037	5.947	<0.0001
c	-24.683	8.198	-3.011	0.0028
d	49.296	7.290	6.762	<0.0001

Notes: diameter and height as measured on the 5 tallest shoots per stump; SE = Standard error; Circumference of the stump at cut level, in mm; Maple = 1 if species is maple, 0 if not; Oak = 1 if species is oak (Q. cerris L. or Q. pubescens L.), 0 if not

Table 2.5 – Insertion of shoots: percent distribution of different types

	Adventitious shoots	Basal shoots	Root suckers
All treatments together – by species			
Species - χ^2 = 10.491; p-Value = 0.033			
Oak	11.0	80.9	8.0
Maple	12.3	82.9	4.8
Ash	**16.0**	78.7	5.2
Oak only – by treatment			
Treatments - χ^2 = 17.008; p-Value = 0.002			
Chainsaw	**16.8**	73.5	9.7
Disc	9.5	82.1	8.4
Shear	**6.5**	88.1	5.5
Maple only – by treatment			
Treatments - χ^2 = 9.571; p-Value = 0.048			
Chainsaw	**17.8**	74.8	7.4
Disc	9.4	87.7	2.8
Shear	9.7	86.3	4.0
Ash only – by treatment			
Treatments - χ^2 = 31.671; p-Value = 0.000			
Chainsaw	23.7	69.1	7.2
Disc	23.3	69.8	7.0
Shear	**3.6**	94.2	**2.2**

Notes: insertion as measured on the 5 tallest shoots per stump; Oak = consolidated data for Q. cerris L. and Q. pubescens L.; Ash = consolidated data for F. angustifolia Vahl and F. ornus L.; numbers in bold represent the largest contributors to the χ^2

Further analyses were conducted after replacing felling technology with damage class as the main independent variable, but none pointed at any significant differences, and therefore the results are not reported in this manuscript. Mechanized cutting had no effect on total N and carbon accumulation in the stump, which followed a classic seasonal pattern (Table 2.6). Total N concentration and C/N ratio showed a substantial steady state for N content in the stumps (Figures 2.4 and 2.5), which varied only with species: oaks had higher N content (0.27 mg g^{-1} dry weight) than ash and maple (0,19 and 0.21 mg g^{-1} dry weight, respectively). After cutting, the soluble sugar and carbon reserves in the ray parenchyma of the stumps decreased, following a well defined seasonal pattern (p-Value <0.001) (Figures 2.6 and 2.7). The highest decrease was recorded between April and July, during sprouting and spring growth (83% and 24% of reduction of the starch and soluble sugar content respectively).

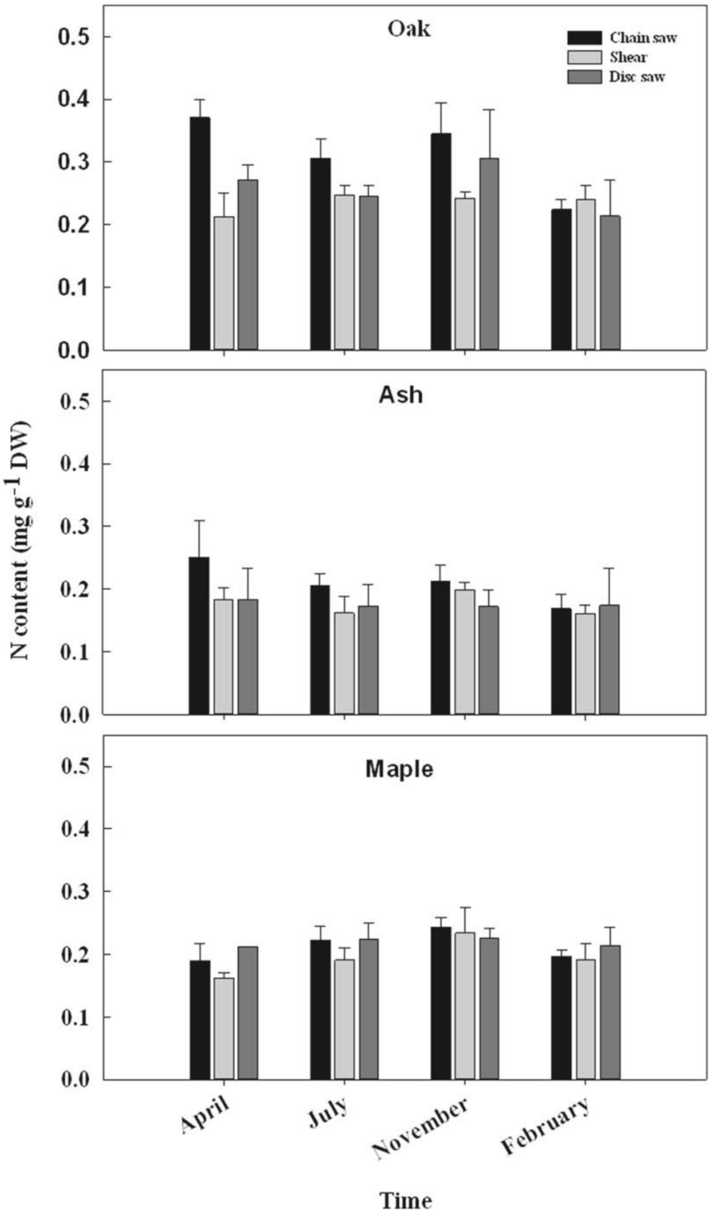
Table 2.6 – Stump nutrient content: repeated-measures ANOVA

		DF	SS	η^2	F-Value	p-Value
Starch	Intercept	1	19978.1	0.79	211.308	<0.0001
	Treatment	2	85.2	0.00	0.450	0.6415
	Species	2	1871.6	0.07	9.898	0.0005
	Treat*Species	4	352.6	0.01	0.933	0.4580
	Residual	31	2930.9	0.12		
	Time	3	27547.9	0.84	222.673	<0.0001
	Time*Treat	6	101.4	0.00	0.410	0.8708
	Time*Species	6	804.5	0.02	3.251	0.0060
	Time*Treat*Species	12	466.8	0.01	0.943	0.5081
	Residual	93	3835.2	0.12		
Soluble sugar	Intercept	1	22824.8	0.78	122.950	<0.0001
	Treatment	2	603.9	0.02	1.627	0.2216
	Species	2	1534.2	0.05	4.132	0.0315
	Treat*Species	4	408.6	0.01	0.550	0.7010
	Residual	20	3712.9	0.13		
	Time	3	4103.7	0.49	32.140	<0.0001
	Time*Treat	6	141.8	0.02	0.555	0.7640
	Time*Species	6	1251.5	0.15	4.901	0.0004
	Time*Treat*Species	12	405.0	0.05	0.793	0.6556
	Residual	60	2553.7	0.30		
Nitrogen	Intercept	1	4.819	0.92	438.319	<0.0001
	Treatment	2	0.024	0.00	1.113	0.3482
	Species	2	0.125	0.02	5.690	0.0111
	Treat*Species	4	0.025	0.00	0.562	0.6932
	Residual	20	0.220	0.04		
	Time	3	0.018	0.05	1.523	0.2177
	Time*Treat	6	0.032	0.10	1.381	0.2370
	Time*Species	6	0.026	0.08	1.110	0.3671
	Time*Treat*Species	12	0.022	0.07	0.463	0.9284
	Residual	60	0.235	0.71		
C:N Ratio	Intercept	1	4863101	0.87	159.336	<0.0001
	Treatment	2	16402	0.00	0.269	0.7671
	Species	2	66829	0.01	1.095	0.3538
	Treat*Species	4	50960	0.01	0.417	0.7941
	Residual	20	610423	0.11		
	Time	3	31943	0.02	0.536	0.6595
	Time*Treat	6	22478	0.02	0.189	0.9789
	Time*Species	6	68673	0.05	0.576	0.7479
	Time*Treat*Species	12	124334	0.09	0.521	0.8926
	Residual	60	1192324	0.83		

Notes: DF = degrees of freedom; SS = sum of squares; η2= ratio between the SS for the specific effect and the total SS

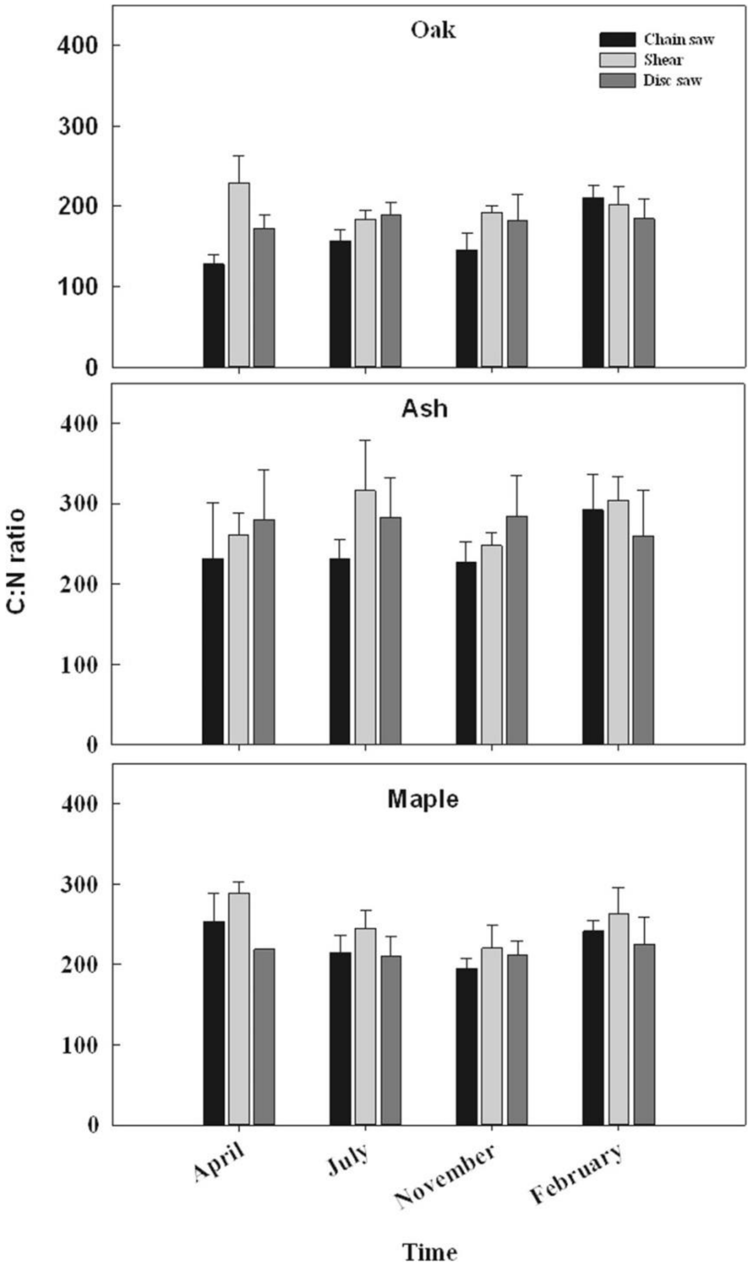
The amount of carbon reserves in the stumps depended on the species (p-Value = 0.03 and <0.0001 for soluble sugar and starch, respectively). Ash showed higher starch and soluble sugar content than oak and maple. The decrease of the carbon reserves occurred at different rates in different species (time x specie, p-Value <0.001). The concentration of soluble sugar remained stable in ash stumps during the whole year, while decreased strongly in response to cutting in oak and maple stumps.

Fig. 2.4 - N concentration in the stumps (mg N per g of dry stump weight) by species, treatment, and month/phenological phase.



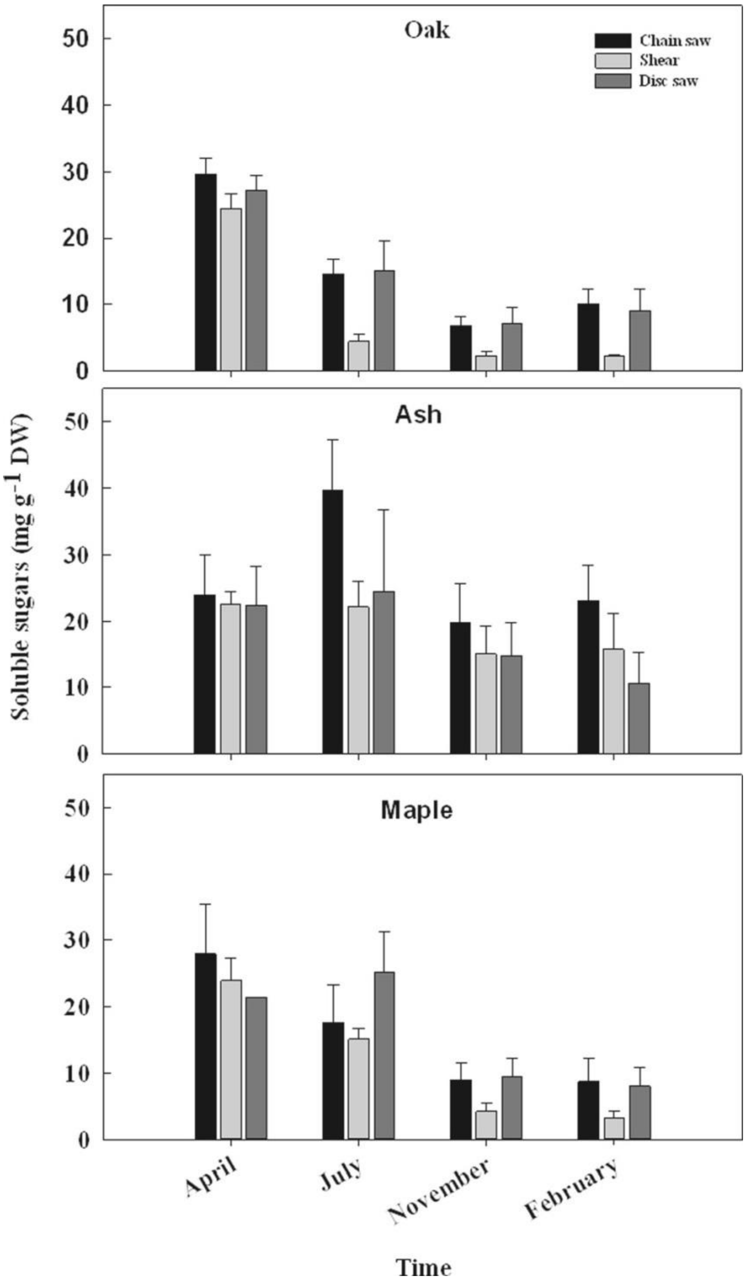
Notes: phenological phases: April = onset after cut, July = exponential growth, November = offset, February = dormancy

Fig. 2.5 - C/N ratio in stumps by species, treatment, and month/phenological phase.



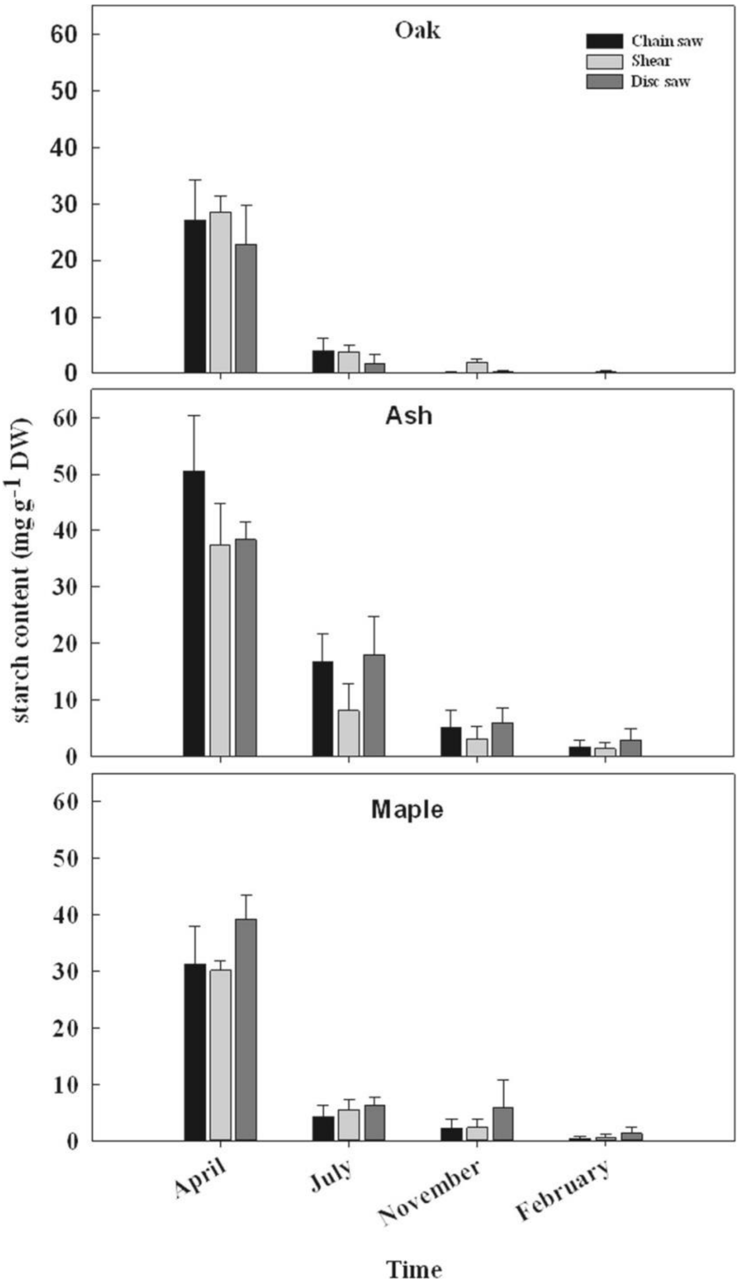
Notes: phenological phases: April = onset after cut, July = exponential growth, November = offset, February = dormancy

Fig. 2.6 - Soluble sugar concentration in the stumps (mg soluble sugar per g of dry stump weight) by species, treatment, and month/phenological phase.



Notes: phenological phases: April = onset after cut, July = exponential growth, November = offset, February = dormancy

Fig. 2.7 - Starch concentration in the stumps (mg starch per g of dry stump weight) by species, treatment, and month/phenological phase.



Notes: phenological phases: April = onset after cut, July = exponential growth, November = offset, February = dormancy

2.5. DISCUSSION AND CONCLUSIONS

Other studies have shown that shears used in coppice produce tall stumps (Spinelli et al. 2007) - taller than obtained with chainsaws or disc saws under the same conditions (Schweier et al. 2015). Theoretically, shears could cut nearer to the soil compared with chainsaws, because they are not as vulnerable to the contact with soil. However, shears cut through a smaller diameter than chainsaws and disc saws of the same size do, and may be forced to cut higher when used on large trees, due to their diameter limitation (Schweier et al. 2015). If that was the case of this study, then one should observe a direct relationship between stump diameter and cutting height (Giudici and Zingg 2005). However, that did not verify: in no case, cutting height was related to stump diameter, nor was it systematically associated with mechanical cutting (Pyttel et al. 2013). In fact, the disc saw (mechanical felling) did not produce taller stumps than the chainsaw (manual felling), which is consistent with the findings of previous studies, although not specific to coppice operations (Hall and Han 2006). A better explanation for the taller stumps produced by the shear is the specific cutting mechanism, which requires engulfing the stem within the full arc described by the closing blades. That might be difficult to achieve when too close to the ground, near the insertion of the stems on the stump. In any case, cutting height is likely affected by a combination of factors, including machine type, tree species, stump diameter and slope gradient (Han and Renzie 2005).

Corroboration from previous studies excludes that the results obtained from this experiment can be attributed to the specific machines, operators or practices observed in the specific case, and allows generalization. Such corroboration is also available for the higher damage level associated with the use of shears (De Souza et al. 2016). Shears produce compression stress (McNeel et al. 1987), which explains both the high incidence of damage and its specific type. Previous studies have shown that the most severe damage types – i.e. crack and stump pull - may be observed on a large proportion of the coppice stumps cut with a shear, which varies between 20% (Spinelli et al. 2014a) and 70% (Schweier et al. 2015).

Our study suggests that severe damage of this type – and especially stump pull – may result in increased stump mortality, as already found by other Authors (De Souza et al. 2016, Ducrey and Turrel 1992).

Fortunately, stump pull is relatively rare (6% here) and it does not automatically result in death. In general, the levels of stump mortality recorded in this study are as low as reported for manual cutting (Ducrey and Turrel 1992, Giudici and Zingg 2005), and lower than reported for the mechanical cutting of aged oak coppice (14-16%; Pyttel et al. 2013) or short-rotation eucalypt coppice (9-19% De Souza et al. 2016). In the latter two cases – however – relatively high mortality was related to old stump age and inappropriate cutting season, respectively. Therefore, the low mortality levels recorded in this study might be considered typical of a healthy coppice forest managed according to good practice.

The height of dominant shoots has already proved a reliable indicator of overall stump vigor (Giudici and Zingg 2005, Pyttel et al. 2013), which supports our choice of indicators. Both the height and the diameter of the dominant shoots indicate that stump vigor is not affected by felling technology, and this statement is supported by the few works appeared on this subject over the years (Crist et al. 1983, Ducrey and Turrel 1992, Pyttel et al. 2013, De Souza et al. 2016). If at all, cutting with shears seems to prompt the emission of a larger number of shoots than obtained when cutting with a saw (Cabanettes and Pagès 1986, Hytönen 1994, De Souza et al. 2016), which verified in our study as well. Our study also found that shoot vigor is directly related to stump size, as reported by Johnson (1975), Ducrey and Turrel (1992) and Souza et al. (2016). Such finding may seem intuitive, but not all authors agree on that (McDonald and Powell 1983, Pyttel et al. 2013). Contradictory results may be sourced to the ambiguous character of stump size as an indicator: while large stump size may indicate vigor, it may also point to the old age of the parent tree, which results in a decreased regeneration ability for some species (Matula et al. 2012).

Current bibliography presents more contradiction when it comes to the relationship between re-sprouting vigor and cutting height. While some authors state that a very low cutting height limits re-sprouting vigor (Cabanettes and Pagès 1986, Giudici and Zingg 2005, Harmer 2004), other support the opposite notion (Ducrey and Turrel 1992). Our findings place us with the large group of those who deny any relationship between cutting height and re-sprouting vigor (Piskoric 1963, Pyttel et al. 2013, Roth and Hepting 1943), despite the relatively large cutting height range explored in our study. During the first growing season, the carbon and nitrogen balance of the stumps were not affected by felling technique, indicating mechanized felling had no detrimental effect on the vigor and nutrient status of the stumps in the short term. Unfortunately, current bibliography offers no other similar experiments that may be used for comparison with these results. Some authors postulate the existence of a linear relationship between biomass produced after cutting and carbon reserves in the stump (Waring and Pitman, 1985). If that is the case, then re-sprouting vigor may be unaffected by felling technique, because that does not alter the nitrogen/carbon reserves in the stumps.

Regardless of cutting technology and species, the initial growth of shoots was associated with the mobilization of previously accumulated starch reserves, which strongly decreased between April and July. The involvement of soluble and insoluble energy reserves within the stumps and coarse roots during the re-sprouting has already been observed in *Eucalyptus* spp (Wildy & Pate 2002) and *Erica* spp (Paula and Ojeda, 2009). On the contrary, N reserves stored in the sapwood did not seem involved in the re-sprouting process, because their concentration remained stable during the season. Our data confirm the assumption that N allocation to storage is regulated by plant phenology more than by environment or wounding (Millard and Grelet, 2010). The amount of N stored in the sapwood was very similar to that found in *Quercus petrea* L. (Andrè and Ponette, 2003), *Quercus robur* L. (Penninckx et al., 2001), *Acer rubrum* L. (Martin et al., 1998) and *Fraxinus mandshurica* Rupr. (Mei et al., 2015). Turkey oak had higher N content than ash and maple, but this significant species effect may have resulted from a different stump size distribution.

The C/N ratio can be considered a valuable index of the decomposition state of angiosperm wood (Weedon et al., 2009). After one growing season the C/N ratio of the stumps remained stable for all felling treatments. Therefore, the high stump damage caused by the shear did not determine any significant changes in the nutrition substrate for decomposers, at least in the short term.

Taken together, the knowledge available on the subject indicates that the issue is quite complex, because coppice stands come in endless types and conditions, and many factors affect coppice regeneration. For this reason, one is hard put to produce general directions. Against this background, our study offers a remarkable insight into the effects of cutting technology on coppice regeneration. As far as one can tell, mechanical cutting does not increase stump mortality or reduce re-sprouting vigor. Of course, this is the result from the first growing season, and one still has to determine if the same trends will continue in the following years.

However, the Authors of past longer-term studies reported that early trends were maintained for at least four or five years, after which differences seemed to even out (Ducrey and Turrel 1992, Giudici and Zingg 2005, Harmer 2004). This study will continue in the next years, and if these finding will be confirmed, one may safely support the mechanization of coppice operations, to the benefits of improved financial sustainability and work safety. That will help unlocking the potential of coppice forests, which represent a large source of renewable biomass and may offer better resistance to the effects of climate change, compared with high forests (Spiecker 2003, Sjölund and Jump 2013).

2.6. REFERENCES

Albizu PM, Tolosana-Esteban E, Roman-Jordan E (2013) Safety and health in forest harvesting operations. Diagnosis and preventive actions. A review. Forest Syst 22: 392-400.

Amorini E, Bruschini S, Cutini A, Di Lorenzo M, Fabbio G (1998) Treatment of Turkey oak (*Quercus cerris* L.) coppices. Structure, biomass and silvicultural options. Annali dell'Istituto Sperimentale per la Selvicoltura 27, 121-129 ISSN 0390-0010.

André F, Ponette Q (2003) Comparison of biomass and nutrient content between oak (*Quercus petraea*) and hornbeam (*Carpinus betulus*) trees in a coppice-with-standards stand in Chimay (Belgium). Ann For Sci 60: 489–502.

Bell J (2002) Changes in logging injury rates associated with use of feller-bunchers in West Virginia. J Safety Res 33: 462-471.

Buckley G P (1992) Ecology and management of coppice woodlands. Chapman & Hall, London.

Cabanettes A, Pagès L (1986) Effet des techniques de coupe sur la hauteur des cépées dans un taillis de châtaignier (Castanea sativa Mill). Can J For Res 16: 1278-1282.

Coppini M, Hermanin L (2007) Restoration of selective beech coppices: A case study in the Apennines (Italy). For Ecol Manag 249: 18-27.

Crist J, Mattson J, Winsauer S (1983) Effect of severing method and stump height on coppice growth. In: Intensive Plantation Culture: 12 Years Research (Hansen EA, ed), USDA Forest Service Gen. Tech. Rep. NC-91, 58-63.

D'Acqui L, Pucci A, Janik L (2010) Soil properties prediction of western Mediterranean islands with similar climatic environments by means of mid-infrared diffuse reflectance spectroscopy. Eur J Soil Sci 61: 865-876.

De Souza D, Gallagher T, Mitchell D. McDonald T, Smidt M (2016) Determining the effects of felling method and season of year on the regeneration of short rotation coppice. Int J For Eng 27: 53-65.

Deslauriers A, Beaulieu M, Balducci L, Giovannelli A, Gagnon M, Rossi S (2014) Impact of warming and drought on carbon balance related to wood formation in black spruce. Ann Bot 114:335-345.

Ducrey M, Turrel M (1992) Influence of cutting methods and dates on stump sprouting in Holm oak (Quercus ilex L) coppice. Ann Sci For 49: 449-464.

Emiliani G, Traversi M, Anichini M, Giachi G, Giovannelli A (2011) Transcript accumulation dynamics of phenylpropanoid pathway genes in the maturing xylem and phloem of *Picea abies* during latewood formation. J Integr Plant Biol 53: 783–799.

Giovannelli A, Emiliani G, Traversi M, Deslauriers A, Rossi S (2011) Sampling cambial region and mature xylem for non structural carbohydrates and starch analyses. Dendrochron 29: 177–182.

Giudici F, Zingg A (2005) Sprouting ability and mortality of chestnut (*Castanea sativa* Mill.) after coppicing. A case study. Ann For Sci 62: 513-523.

Glithero N, Wilson P, Ramsden S (2013) Prospects for arable farm uptake of Short Rotation Coppice willow and miscanthus in England. Appl Energ 107: 209-218.

Hall R, Han HS (2006) Improvements in value recovery through low stump heights: mechanized versus manual felling. West J Appl For 21: 33-38.

Han HS, Renzie C (2005) Effect of ground slope, stump diameter and species on stump height for feller-buncher and chainsaw felling. Int J For Eng 16: 81-88.

Harmer R (2004) Restoration of neglected hazel coppice. Forestry Commission Information Note 56. Edinburgh, Scotland, UK. 12 p.

Hédl R, Kopecky M, Komàrek J (2010) Half a century of succession in a temperate oakwood: from species-rich community to mesic forest. Divers Distrib16: 267–276.

Hytönen J (1994) Effect of cutting season, stump height and harvest damage on coppicing and biomass production of willow and birch. Biomass Bioenerg 6: 349-357.

Jansen P, Kuiper L (2004) Double green energy from traditional coppice stands in the Netherlands. Biomass Bioenerg 26: 401–402.

Johnson P S (1975) Growth and structural development of red oak sprout clumps. For Sci 21: 413–418.

Kays S, Canham C (1991) Effect of time and frequency of cutting on hardwood root reserves and sprout growth. For Sci 37: 524-539.

Matula R, Svátek M, Kůrová J, Úradníček L, Kadavý J, Kneifl M (2012) The sprouting ability of the main tree species in Central European coppices: implications for coppice restoration. Eur J For Res 131:1501-1511.

MacDonald J, Powell G (1983) Relationships between stump sprouting and parent-tree diameter in sugar maple in the 1st year following clear-cutting. Can J For Res 13: 390–394.

Martin J, Kloeppel B, Schaefer T, Kimbler D, McNulty S (1998) Aboveground biomass and nitrogen allocation of ten deciduous southern Appalachian tree species. Can J For Res 28: 1648-1659.

Mei L, Xiong Y, Gu J, Wang Z, Guo,D (2015) Whole‐tree dynamics of non‐structural carbohydrate and nitrogen pools across different seasons and in response to girdling in two temperate trees. Oecolog 177: 333-344.

McEwan A, Magagnotti N, Spinelli R (2016) The effects of number of stems per stool on cutting productivity in coppiced Eucalyptus plantations. Silva Fenn 50, article id 1448. 14 p.

McNeel J, Czerepinski F (1987) Effect of felling head design on shear-related damage on Southern yellow pine. South J Appl For 11: 3-6.

Millard P, Grelet G (2010) Nitrogen storage and remobilization by trees: ecophysiological relevance in a changing world. Tree Physiol 30: 1083–1095.

Ollikainen M (2014) Forestry in bioeconomy – smart green growth for the humankind. Scand J For Res 29: 360-366.

Olsen E, Hossain M, Miller M (1998) Statistical Comparison of Methods Used in Harvesting Work Studies. Oregon State University, Forest Research Laboratory, Corvallis, OR. Research Contribution n° 23. p. 31.

Paula S, Ojeda F (2009) Belowground starch consumption after recurrent severe disturbance in three resprouter species of the genus Erica. Bot 87: 253-259.

Penninckx V, Glineur S, Gruber W, Herbauts J, Meerts P (2001) Radial variations in wood mineral element concentrations: a comparison of beech and pedunculate oak from the Belgian Ardennes Ann For Sci 58: 253–260.

Piskoric O (1963) The dynamics of height increment of coppice shoots of Evergreen oak. Sumarski List 87: 122-133.

Pyttel P, Fischer U, Suchomel C, Gärtner S, Bauhus J (2013) The effect of harvesting on stump mortality and re-sprouting in aged oak coppice forests. For Ecol Manag 289: 18-27.

Roth E, Hepting G (1943) Origin and development of the oak stump sprouts as affecting their likelihood to decay. J For 41: 27-36.

Schier G, Zasada J (1973) Role of carbohydrate riserve in the development of root suckers in Populus tremuloides. Can J For Res 3: 243-250.

Schweier J, Spinelli R, Magagnotti N, Becker G (2015) Mechanized coppice harvesting with new smallscale feller-bunchers: Results from harvesting trials with newly manufactured felling heads in Italy. Biomass Bioenerg 72: 85-94.

Sjölund J, Jump A (2013) The benefits and hazards of exploiting vegetative regeneration for forest conservation management in a warming world. For 86: 503-513.

Spiecker H (2003) Silvicultural management in maintaining biodiversity and resistance of forests in Europe—temperate zone. J Environ Manag 67: 55–65.

Spinelli R, Cacot E, Mihelic M, Nestorovski L, Mederski P, Tolosana E (2016) Techniques and productivity of coppice harvesting operations in Europe: a metaanalysis of available data. Paper accepted for publication on Ann For Sci

Spinelli R, Ebone A, Gianella M (2014) Biomass production from traditional coppice management in northern Italy. Biomass Bioenerg 62: 68-73.

Spinelli R, Cuchet E, Roux P (2007) A new feller-buncher for harvesting energy wood: Results from a European test programme. Biomass Bioenerg 31: 205-210.

Suchomel C, Spinelli R, Magagnotti N (2012) Productivity of processing hardwood from coppice forests. Croat J For Eng 33: 39–47.

Waring R, Pitman G (1985) Modifying lodgepole pine stands to change susceptibility to mountain pine beetle attack. *Ecol* 66: 889-897.

Weedon J, Cornwell W, Cornelissen J, Zanne A, Wirth C, Coomes D (2009) Global meta-analysis of wood decomposition rates: a role for trait variation among tree species? Ecol Lett 12: 45–56.

Wildy D, Pate J (2002) Quantifying above- and below-ground growth responses of Western Australian Oil Mallee, Eucalyptus kochii subs. plenissima, to contrasting decapitation regimes. Ann Bot 90:185–197.

Wolfslehner B, Krajter S, Jovic D, Nestorovski L, Velichkov I (2009) Framing stakeholder and policy issues for coppice forestry in selected central and south-eastern European Countries. Silva Balc 10: 21-34.

CHAPTER 3 – A low-investment technology for the simplified processing of energy wood from coppice forests

3.1. ABSTRACT

A grapple saw is a low-cost implement, consisting of a hydraulic chainsaw mounted on the frame of a standard log grapple. Grapple-saws are generally installed on forwarders, loaders or modified excavators and are used for cross-cutting whole trees or delimbed stems, often as part of a more complex work task such as pre-bunching, loading or stacking. The study analyzed eight different commercial operations where trees where processed with grapple-saws, instead of dedicated cut-to-length processors. All machines in the study were mounted on excavators, but were used under a wide range of stand types and work conditions. Work productivity was determined with time study techniques, which covered the processing of 1800 trees for a total time of 73 hours. Productivity ranged between 0.8 and 13 dry t per productive machine hour (PMH) or between 0.7 and 11 dry t per scheduled machine hour (SMH), depending on whether delays were excluded or included, respectively. Regression analysis allowed modeling productivity as a function of significant variables, such as tree size, machine type and processing quality. The productivity of coarse processing rapidly increased with tree size until the optimum value of 0.3 dry t per tree, then it slowly declined. The same trend was found for quality processing, but in this case optimum tree size was 0.6 dry t per tree. Productivity was higher for landing site work, cold deck operations and coarse processing into tree sections. A dedicated cut-to-length processor is a better choice for matching tight log product specifications, while the grapple saw is best for negotiating firewood and chip wood. A grapple saw is a low-investment piece of equipment for mechanizing small scale operations, to the benefits of increased productivity, lower processing cost and improved worker safety.

3.2. INTRODUCTION

Coppice management is a widespread forestry practice whereby stand regeneration is obtained from the re-sprouting of cut stumps, rather than from the establishment of new trees from seed. For this reason, coppice management is only suited to tree species that can sprout new shoots from their stumps after cutting, like most hardwoods, especially if the interval between cuts does not exceed 50 or 60 years. Coppice management offers the benefits of simplified care, prompt regeneration and short waiting time; its main drawback is in offering relatively small trees, which are only suitable for the production of pulpwood, fencing assortments and energy wood (Buckley, 1992). As a main source of firewood, coppice stands were very common in the European countryside until the advent of fossil fuels (Hédl, Kopecký, & Komárek, 2010). After that, interest in coppice management has faced a steady decline, leading to abandonment and conversion into high forest. Nevertheless, coppice management still persists on large forest areas, which are estimated at over 26 million hectares in the EU and its neighbors (V.-N. Nicolescu, Pyttel, & Bartlett, 2015).

A new and interesting opportunity for expanding the active management of coppice stands is offered by the modern bio-economy, which is generating a large and sustained demand for biomass feedstock (Matula et al., 2012). Coppice forests are ideally suited for supplying this market with significant amounts of wood, if production can be achieved at competitive conditions (Jansen & Kuiper, 2004). In particular, harvesting cost must be reduced, while increasing operator safety and comfort (Picchio, Maesano, Savelli, & Marchi, 2009). A dramatic improvement in this direction is only obtained through mechanization, which has a multiplier effect on operator productivity and offers a much safer and comfortable work station than can ever be found for the motor-manual work techniques that characterize traditional coppice harvesting (Spinelli, Cacot, et al., 2016).

Unfortunately, the mechanization of coppice harvesting operation is especially challenging, because coppice forests produce relatively small trees, which grow in clumps and have a marked basal sweep (Cacot, 2010). That hinders mechanical felling and may result in increased time consumption and occasional stump damage (McEwan, Magagnotti, & Spinelli, 2016). On top of that, broadleaf trees often present heavy branching, which makes mechanized delimbing and bucking especially difficult (Suchomel, Becker, & Pyttel, 2011). Taken together, the characteristics of coppice trees severely restrict harvester productivity, compared with the levels achieved in softwood stands (Labelle, Soucy, Cyr, & Pelletier, 2016).

However, there is no reason to use a standard harvester when producing energy wood, which is normally subject to very lax size specifications. Firewood is produced with any tree portion having a diameter above 5 cm, and it is cut in approximate lengths, so that diameter and length measurement accuracy is immaterial (Laina, Tolosana, & Ambrosio, 2013). The size specifications for chipwood are even more yielding, and the only processing that is required consists in reducing tree length and bulk to facilitate mechanical handling (Hanzelka, Bolding, Sullivan, & Barrett, 2016). That authorizes use of simpler and cheaper machines than conventional cut-to-length harvesters. In particular, felling can be performed with one of the many small-scale fellers and feller-bunchers currently available on the market (Chakroun, Bouvet, Ruch, & Montagny, 2016), whereas cursory size reduction can be performed with a grapple saw, which is much simpler and cheaper than a conventional cut-to-length processor (Magagnotti, Picchi, & Spinelli, 2013). A grapple saw consists of a standard log grapple equipped with a hydraulic saw, and allows crosscutting as a separate task, or as part of another task, such as pre-bunching, loading or stacking (Pottie & Guimier, 1986). Grapple saws are offered by several manufacturers, and can be purchased as a complete implement or as a stand-alone hydraulic saw designed for mounting on a range of log grapples with suitable size.

While several peer-review papers offer reliable figures about the performance of fellers and feller bunchers used in coppice operations (Schweier et al., 2015; Spinelli, Cuchet, & Roux, 2007), information about grapple saws is still scarce and in the form of preliminary reports (Ruch, Montagny, Bouvet, Ulrich, & Geor, 2016). Therefore, the goal of this study was to produce a first scientific evaluation of grapple-saw productivity and cost, when used to process small trees. A further goal of this study was to identify the main parameters affecting grapple saw productivity, and to suggest improvements to grapple saw use and design.

3.3. MATERIALS AND METHODS

The experiment consisted of the observational study of eight commercial operations where grapple saws were used for processing pre-felled trees or stem-lengths. The study operations were located across Northern and Central Italy, which allowed covering a wide range of working conditions (Figure 3.1).

Coppice harvesting accounted for five of the operations analyzed, while two operations represented young transitional high forests obtained from coppice conversion and only one occurred in a conifer plantation (Table 3.1). Stand age ranged between 20 and 80 years. A binary classification was used to categorize each operation based on work site, work organization and processing quality. This classification was created in order to evaluate the effect of working conditions on machine performance.

Work site was differentiated between "stump site" and "landing", depending on whether the grapple saw unit was processing trees in the forest before extraction, or at a landing after extraction. Work organization was classified as "hot deck" when processing occurred in a sequence with some other operation without a buffer in between (e.g. working under a yarder and processing trees as they arrived at the landing), and as "cold deck" when a large enough feedstock buffer was interposed between the processing unit and any other units operating upstream and downstream from it (e.g. working tree bunches left at the stump site, after all felling has been completed). Processing was categorized as "coarse" processing when trees were cut in random lengths without paying much attention to exact product measurement and branch reduction (e.g. tree sections), and as "quality" processing when trees were turned into multiple assortments according to relatively strict product specifications.

Each operation represented a separate company and machine, which allowed covering a wide range of equipment (Figure 3.2). All grapple saws in the study were mounted on excavators, with a mass ranging between 5 and 20 t. Saw cut capacity varied from 50 to 80 cm, and was closely associated with the mass and power of the base machine (Table 3.2).

Fig. 3.1 - Map of case study locations

Fig. 3.2 - Sample snapshots from different operations (numbers refer to operation #)

Table 3.1 - Description of the test sites

Operation	Place	stand	species	age	work site	deck	Product	Processing
1	Graglia	coppice	O, C, L	45	Stump site	Hot	6 m - long firewood	Coarse
2	Pontepetri	coppice	C, L	30	Landing	Hot	Posts, firewood, chips	Quality
3	Mazzè	coppice	L	25	Stump site	Cold	2.4 m - long firewood	Quality
4	Passo dei Carpinelli	high forest	F, P	70	Stump site	Hot	2.5 / 3 m logs	Quality
5	San Pietro al Natisone	coppice	B, H, C	60	Landing	Cold	4 m - long firewood	Coarse
6	Guasticce	coppice	TO	34	Stump site	Cold	Tree sections	Coarse
7	Santomoro	coppice	C, B	20	Landing	Cold	Posts, firewood, chips	Quality
8	Castel S. Angelo s. Nera	high forest	B	80	Landing	Hot	3 m - long firewood	Coarse

Notes: O = oaks and namely: red Oak, (*Quercus rubra* L.) and common oak (*Quercus robur* L.); L = black locust (*Robinia pseudoacacia* L.); C = chestnut (*Castanea sativa* Mill.); F = fir (*Abies alba* Mill.); P = pine (*Pinus nigra* J.F.Arnold); B = beech (*Fagus sylvatica* L.); H = hornbeam (*Ostrya carpinifolia* Scop.); TO = Turkey oak (*Quercus cerris* L.)

Table 3.2 - Machine characteristics

Operation	Excavator	Type	Kg	kW	Grapple	Saw	Cut length (cm)
1	Neuson12002	Tracked	11500	73	Interlam IT 1600 PF	interlam IT700CTH	70
2	Komatsu PC 75	Tracked	7600	50	Gripen HSP 025	Gripen saw GSK / 75	70
3	Fiat Hitachi EX 135	Tracked	13300	66	Hultdins super grip 360s	Hultdins super saw 550	70
4	Komatsu pc110r	Tracked	10500	71	SVA BTO 1600	interlam IT800MS	70
5	Liebherr 904 litronic	Rubber tired	20500	99	Gripen HSP 035	Gripen saw GSK / 82	80
6	Komatsu PC138US-8	Tracked	13600	68	Hultdins SGII-360R	COMAF IT800MS	70
7	Komatsu PC 75	Tracked	7600	50	Interlam IT 1300 PF	Interlam IT 500 CTH	50
8	JCB 8052	Tracked	5200	34	Interlam IT 1300 PF	Interlam IT 500 CTH	50

All trials were conducted between January 2016 and June 2017. Each trial consisted in a time and motion study (Magagnotti & Spinelli, 2012). The observational unit was the single work cycle, defined as the time spent to turn one or (usually) more trees into a bunch of tree sections or into several piles of different assortments. In one case (operation #7), the grapple saw unit handled stem-lengths and therefore the cycle was defined as the processing of one or more stem-lengths into cut-to-length logs. Logs and tree sections were often stacked onto bigger piles, as part of the work sequence.

For each cycle, researchers measured product mass output and work time input, with their quotient representing productivity. Mass output was estimated using the equations reported by Tabacchi et al. (2011) for Italian tree species, based on specific data about: species, diameter at breast height (DBH) and total tree height. To this end, the species of each tree processed in a cycle was noted, and the DBH was determined individually using a conventional forest caliper. Tree height was estimated based on DBH, after building a DBH to height curve for each stand on the basis of 30 sample trees distributed across the full range of DBH values. In this instance, DBH was also determined with a forest caliper, whereas height was determined with a tape or with a vertex hypsometer, depending on whether cut trees or standing trees were the easiest to access. The tables returned the dry mass of the stem and branches, down to a 5 cm small end diameter. Average tree size (expressed as dry mass) was obtained as a quotient between total mass and number of trees per cycle.

Time input was determined with a classic time study, using a Husky Hunter hand-held field computer running the dedicated Siwork3 time study software (Kofman, 1995). Work time was split among different functional activities with clearly recognizable starting and ending points, namely: grabbing the unprocessed tree (or trees); processing it (or them) into tree sections or other assortments; piling the sections or assortments; moving to the next tree bunch; other work. Delays were recorded separately and categorized as operational, personal and mechanical (Björheden, 1991). Machine costs were calculated with the method described by Miyata (1980), for an estimated annual utilization of 800 scheduled machine hours (SMH), which was the average reported by the study operators. This value was considered smaller than reported for dedicated forestry equipment (Malinen, Laitila, Väätäinen, & Viitamäki, 2016), but still representative of small-scale operations in

Mediterranean forestry (Spinelli, Magagnotti, & Picchi, 2010). Insurance and tax fees were estimated at 2500 € year^{-1}, while interest rate was set at 4%. Investment cost, fuel consumption, service life and resale price were obtained directly from each individual machine owner. Labor cost was estimated at 20 € SMH^{-1} , based on the unionized wages for specialized operators. This was done with the aim to assure consistency across the study. Hourly machine rate ranged between 46 and 67 € h^{-1}, with a mean value of 56 € h^{-1} (Table 3.3).

Study data were analyzed with Statview 5.01 Advanced Statistics Software. Preliminary analyses included descriptive statistics and distribution tests. The normality of data distribution was checked using the Shapiro-Wilk test, while Bartlett's test was used to assess homoscedasticity.

Most of the data did not meet the parametric assumptions, and therefore the statistical significance of any differences between treatments was tested using non parametric techniques. Multiple linear regression analysis was used to describe significant relationships between productivity and selected independent variables, such as tree size, number of tree per cycle and work conditions - the latter introduced within the regression as dummy variables (Olsen, Hossain, & Miller, 1998). All tests were conducted for a significance $\alpha < 0.05$.

The study contained data for 603 cycles and included 73.3 hours of valid cycle time. During this period, the 8 selected machines processed 1800 trees, or 308 t dry wood.

3.4. RESULTS

Median productivity values were 5.8 dry t PMH^{-1} and 4.8 dry t SMH^{-1}, for a median tree size equal to 0.175 dry t. However, productivity figures ranged between 0.8 and 13 dry t per productive machine hour (PMH) or between 0.7 and 11 dry t per scheduled machine hour (SMH), depending on whether delays were excluded or included, respectively (Table 3.4). Such high variability depended on widely variable machine and site characteristics.

First and foremost, productivity was strongly impacted by individual tree size, despite the dampening effect of mass handling. Machine size also had a strong and significant effect on productivity, with small machines (grapple saw cutting capacity $\leq$ 50 cm) recording a lower productivity than the rest. Small grapple saws were installed on small excavators (<8 t), which had less power and stability than larger machines, and therefore grabbed smaller loads, took longer to cut through a stem or bunch, and had to move with more caution to avoid overturning. Work site, work organization and processing quality also had a marked effect on productivity and delay incidence (Table 3.5). In particular, work organization had the strongest effect on the incidence of delays, while processing quality had the highest impact on net work productivity. Scheduled productivity was significantly higher for the machines that worked in a cold deck operations and renounced quality processing. Verification was obtained from operations 5 and 6, which were by far the most productive and were characterized by the coarse processing of relatively large trees in a cold deck operation. In contrast, the exceptionally low productivity recorded for operation 7 was associated with the quality processing of very small stems. Quality processing required large manual inputs, as the operator had to leave his cab to trim branches with a chainsaw or measure log lengths and mark crosscutting points on the stems. Work site (stump site or landing) had a strong effect on both net productivity and delay incidence, but these effects went in the opposite directions. The better terrain conditions encountered at the landing boosted net productivity, but the inevitable interaction with other units also increased the incidence of delays. The two effects balanced each other, so that scheduled productivity did not differ significantly with work site.

The incidence of delays was widely variable and ranged between 13% and 56% of total worksite time, with mean utilization amounting to 72% (Figure 3.3). Three quarters of delay time were represented by operational delays, especially waiting. Mean delay incidence was 18% and 39% for cold deck operations and hot deck operations, respectively: that translated into delay factors equal to 0.21 and 0.63 (Zimbalatti & Proto, 2009). Mechanical availability during the study averaged 96%.

Except for operation 7, only 4% of total work site time was spent for manual processing activities, which highlighted the technical effectiveness of the grapple saw. The exceptionally high manual input recorded for operation 7 was associated with conversion into many different assortments, in an attempt to maximize value recovery. Some of these assortments presented tight quality specifications and required exact length measurement and precise branch trimming. As a result, the operator spent as much time with the chainsaw as he did with the grapple saw, and productivity was much lower than recorded for the other operations.

Table 3.3 - Machine costing

Operation	#	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Investment	€	106,9	61	115	101,9	141,7	111,4	63,9	73,9
Resale	€	29,225	16,75	32,05	27,725	31,425	31,65	21,475	23,475
Service life	Years	10	10	10	10	10	10	10	10
Utilization	SMH year^{-1}	800	800	800	800	800	800	800	800
Interest rate	%	4%	4%	4%	4%	4%	4%	4%	4%
Depreciation	€ year^{-1}	8,19	4,7	8,92	7,84	11,32	8,51	4,59	5,39
Interests	€ year^{-1}	2,802	1,594	2,994	2,665	3,63	2,924	1,73	1,986
Insurance	€ year^{-1}	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5
Diesel	€ year^{-1}	5,08	3,176	6,352	5,08	5,08	6,776	3,176	2,544
Lube	€ year^{-1}	508	318	635	508	508	678	318	254
Repairs	€ year^{-1}	4,095	2,35	4,46	3,92	5,66	4,255	2,295	2,695
Machine cost	€ SMH^{-1}	29	18	32	28	36	32	18	19
Crew	n°	1	1	1	1	1	1	1	1
Labour	€ SMH^{-1}	20	20	20	20	20	20	20	20
Overheads	€ SMH^{-1}	10	8	10	10	11	10	8	8
Total cost	€ SMH^{-1}	59	46	63	58	67	62	46	47

Notes: SMH = scheduled machine hours, including delays

Table 3.4 - Main results of the study

Operation	**#**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Cycles	n°	68	55	79	69	90	217	17	8
Trees	n°	178	278	311	69	268	336	231	129
Tree size	dry Kg tree^{-1}	254	58	63	324	395	228	27	124
Mass	dry t	45.3	16.1	19.7	22.3	106.0	76.6	6.3	15.9
Productivity	dry t PMH^{-1}	5.6	4.4	4.6	3.1	13.0	8.1	0.8	4.2
Productivity	dry t SMH^{-1}	3.6	2.4	4.0	2.2	10.9	6.7	0.7	1.8
Unit Cost	€ dry t^{-1}	17	34	29	18	6	4	75	27

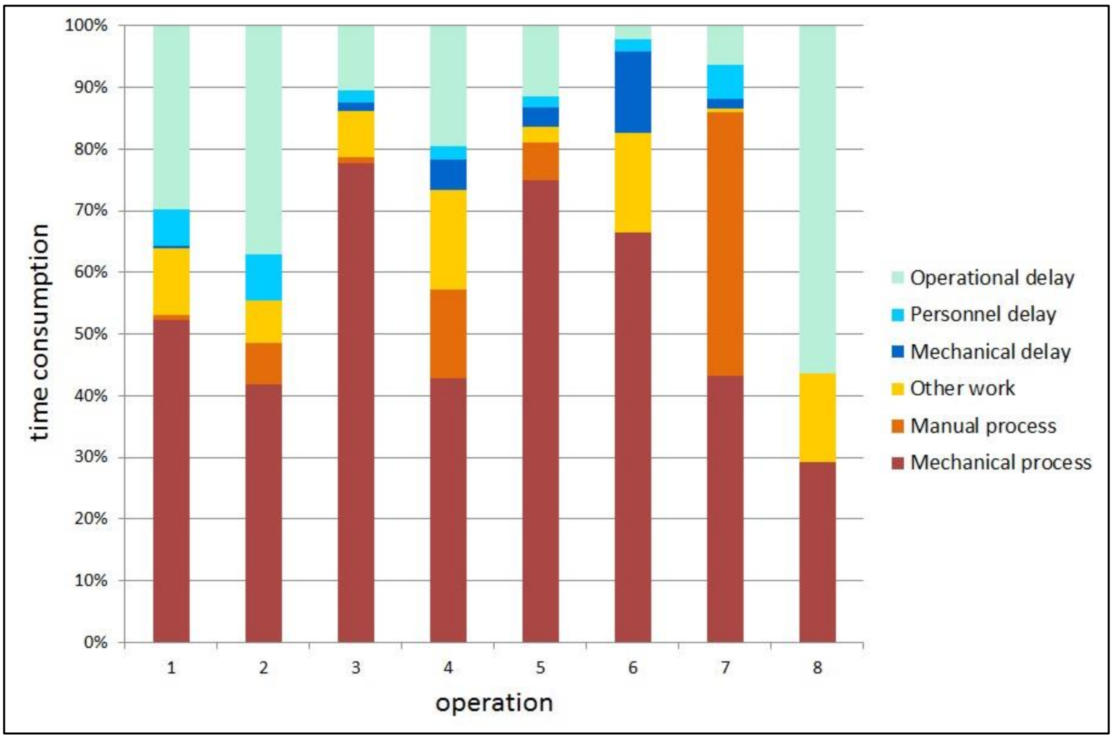
Notes: productivity = grand mean (total mass/total time); PMH = productive machine hours, excluding delays; SMH = scheduled machine hours, including delays

Table 3.5 - Median values for productivity and delay incidence, as a function of work site, work organization, processing quality and machine type (saw cutting capacity)

Work site		**Stump**	**Landing**	**p-Value**
Productivity	dry t PMH^{-1}	5.4	8.5	<0.0001
Productivity	dry t SMH^{-1}	4.6	5.9	0.2680
Delays	%	10.9	23.1	<0.0001
Work organization		**Hot**	**Cold**	**p-Value**
Productivity	dry t PMH^{-1}	4.1	7.6	<0.0001
Productivity	dry t SMH^{-1}	2.7	6.8	<0.0001
Delays	%	28.2	7.5	<0.0001
Processing quality		**High**	**Coarse**	**p-Value**
Productivity	dry t PMH^{-1}	3.7	8.8	<0.0001
Productivity	dry t SMH^{-1}	2.9	7.3	<0.0001
Delays	%	18.4	12.1	<0.0001
Saw cutting capacity		**≤50 cm**	**>50 cm**	**p-Value**
Productivity	dry t PMH^{-1}	1.1	6.0	<0.0001
Productivity	dry t SMH^{-1}	0.9	5.0	<0.0001
Delays	%	25.6	13.9	<0.0001

Notes: PMH = productive machine hours, excluding delays; SMH = scheduled machine hours, including delays; P-Value = significance according to Mann-Whitney's non-parametric test; Delay incidence is described by the mean - not the median - because of the erratic occurrence of delays (most data points = 0), which makes the median an even less useful descriptor than the mean

Fig. 3.3 - Breakdown of work time



Regression analysis allowed modeling net work time per cycle as a function of the main independent variables. The analysis confirmed the fundamental effect of tree size, machine size, number of trees per cycle and processing quality on net work time per cycle (Table 3.6). The model showed that tree size and number of trees per cycle had a direct effect on time consumption, while the effect of processing quality was mediated by the number of trees in a cycle. A separate equation was provided for estimating the number of trees per cycle as a function of tree volume: managers can obtain the average tree volume from inventory data, while they are much less likely to estimate correctly the number of trees handled in a machine work cycle. Therefore, this second equation was designed to assist users in making an informed guess about the expected number of trees per cycle, if machine type and crew skills reflected those represented in the study. The low coefficient of determination of this second model pointed at its general indicative value, rather than at a strict predictive function. In fact, a weak relationship was probably better than a strong one, which would have pointed at a critical intercorrelation between the independent variables used for the time prediction model.

Used together, the models showed that productivity grew with piece size until reaching optimum tree mass, and then declined. Different curves were obtained for different work quality targets (Figure 3.4) and machine types (Figure 3.5). Net productivity could be turned into scheduled productivity by multiplying the result by expected utilization. The effect of work organization could be gauged by applying utilization values of 0.82 and 0.61 for cold deck and hot deck operations, respectively.

Processing cost varied from 4 to 75 € dry t^{-1}, or from 4 to 34 € dry t^{-1} if operation 7 was excluded. In that case, mean processing cost amounted to 19 € dry t^{-1}. The processing cost recorded for operation 7 was twice as high as the highest cost found among the remaining operations.

Table 3.6 - Time consumption and number of pieces per cycle as a function of significant independent variables (regression models)

Work time = a t ss + b N° + c N° High + d N° Small

R^2 adj = 0.768; n = 563; F = 465.679; p <0.0001

	Coeff	SE	t-Value	P-Value
a	415.330	34.963	11.879	<0.0001
b	51.260	4.037	12.696	<0.0001
c	350.411	73.433	4.772	0.0014
d	36.173	4.790		<0.0001

N° = a + b t ss^2 + c t ss

R^2 adj = 0.116; n = 563; F = 37.709; p <0.0001

	Coeff	SE	t-Value	P-Value
a	4.797	0.251	19.097	<0.0001
b	5.182	1.262	-7.502	<0.0001
c	-9.467	1.112	4.658	<0.0001

Notes: productive work time and process time = s $cycle^{-1}$; t ss = piece weight in dry tons; N° = number of pieces per cycle; High = indicator variable for high quality processing: if high quality processing = 1, if not = 0; n = number of valid observations; SE = Standard error; Small = indicator variable for small size machine (saw cut ≤ 50 cm): if small = 1, otherwise = 0

Fig. 3.4 - Net work productivity for a medium size machine (> 5t) as a function of tree size and processing quality

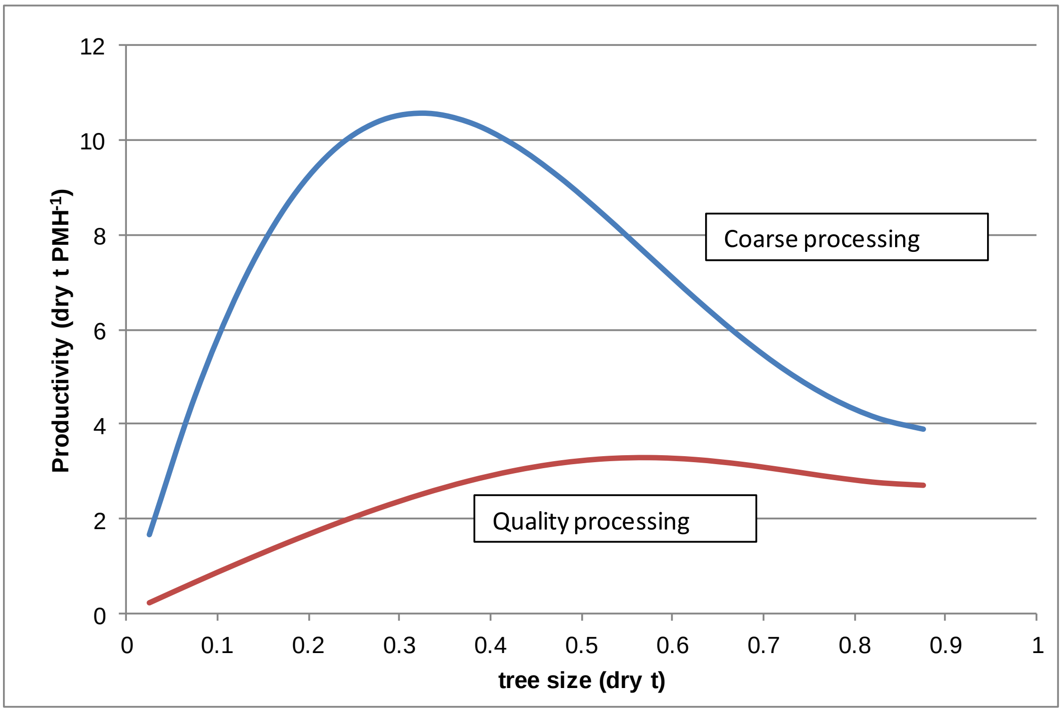
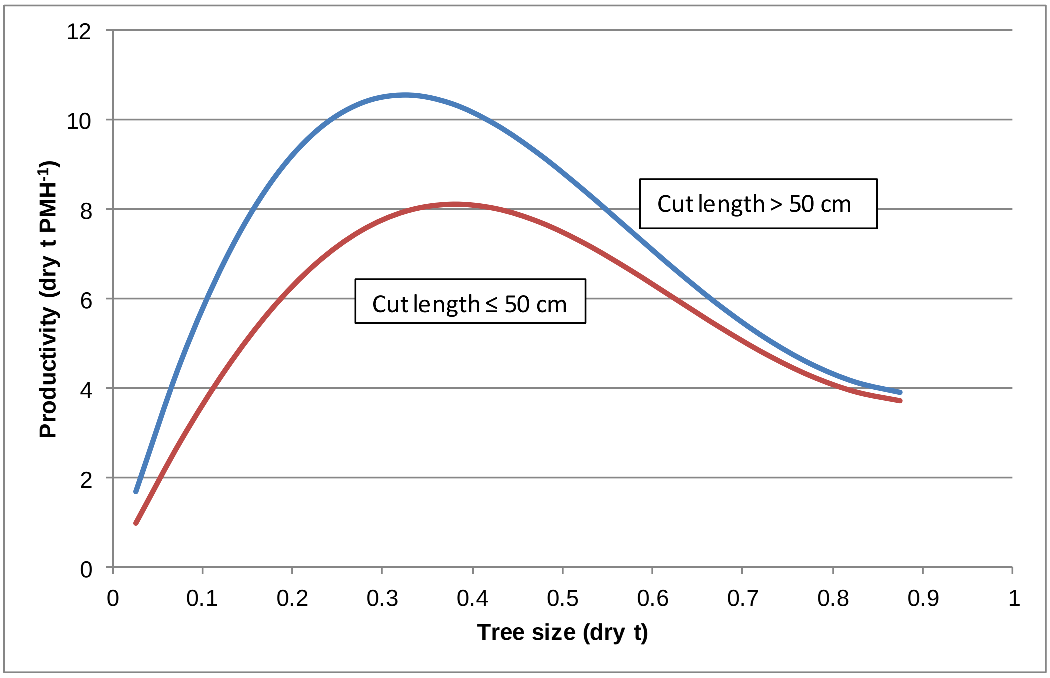


Fig. 3.5 - Net work productivity for coarse processing as a function of tree size and machine cutting capacity



3.5. DISCUSSION

First of all, it is important to state upfront the main limitation of the study, which lays in the observational character. This was the inevitable consequence of relying on commercial operations, as required for reflecting realistic work conditions, for sampling multiple teams and machines, and for containing study cost within budget limits. Such study would have not been financially sustainable if experimental conditions had to be controlled. In fact, the relatively large number of observations gathered with this study is likely to counteract the shortcomings of an unbalanced dataset, which is a typical flaw of observational studies. Treatment balance is especially critical to small datasets, while large datasets are less sensitive to imbalance (Payne, 2003). Nevertheless, data imbalance obfuscated the effects of some of the study variables and decreased model resolution. In particular, data imbalance may explain why the regression models could not account for the effect of work site, which would have been logical and was suggested by the raw data, but without statistical corroboration.

On the other hand, the observational design of the experiment allowed covering a wide range of machine types and work conditions, which support generalization of results. The study also spanned over a full spectrum of tree sizes, from 25 to 450 kg dry weight. In fact, the very wide range of tree size figures included in the study allowed finding the "sweet spot" for the use of grapple saws, which is clearly shown in Figures 4 and 5 (Visser & Spinelli, 2012).

The productivity model obtained from this study is logical and relatively easy to explain. Productivity increases with tree size until optimum values are reached, then declines steadily while still remaining above the initial values recorded for very small trees. Of course, users must be cautioned again extrapolation of the model results beyond the range of tree sizes used for estimating it, which varies from 0.01 and 0.8 dry t. The model has a quadratic component, which may return unrealistic results for extreme input values. In that regard, it is interesting to notice that optimum tree size is higher for quality processing than for coarse processing, which points at a larger compensation effect of tree size when time consumption increases.

The effects of quality processing and grapple capacity combine with the number of trees handled in cycle: quality processing is best applied to few trees at a time, proportional to grapple size.

Most important, the model quantifies the performance decline associated with the elaborate processing of quality assortments, which helps answering the question about whether a grapple saw is only suited for coarse processing and should be replaced with a more sophisticated cut-to-length processor when trees must be turned into assortments with exact size specifications. While this study is not a comparative one, productivity data for the use of processors with small hardwood stems are abundant, and one may attempt a preliminary comparison. A good match is offered by Suchomel et al. (2012), who describe the productivity of a medium size excavator when handling coppice stems that are very similar to those observed in this study. For a medium tree size equal to 0.1 dry t, the processor in that study achieved a productivity of 3.8 dry t PMH^{-1}, while the mean grapple saw in this study only produced 0.9 dry t PMH^{-1} (quality processing). Therefore, used under similar conditions, a processor is up to 4 times more productive than a grapple saw, but only twice as expensive to run, which results in a dramatic saving on processing cost. Of course, this comparison cannot be conclusive, because conducted for different machines, sites and operators: yet, it supports the notion that grapple saws are best used for coarse processing of energy wood, and that specialized CTL processors should be deployed when quality processing is required, as when producing posts and fencing assortments. That casts some doubts on the functional use of translating grapple saws, i.e. saws mounted on grapples through an hydraulically operated sliding assembly that allows adjusting the distance between the saw and the grapple frame to match exact crosscutting marks. These machines are designed for precise bucking of pre-marked delimbed stems, but they are deployed in special cases only (Spinelli et al., 2011), and their capabilities should be further explored.

While processors are definitely more efficient than grapple saws when it comes to quality processing, grapple saws could still be preferred for this task when detached to assist a yarder in low-quality stands, as the many coppice forests growing on steep terrain (Zimbalatti & Proto, 2009). In that case, the productivity of a specialized cut-to-length processor is so much higher than the productivity of a yarder that the processor is forced to long waiting times. Therefore, it does not really matter if quality processing by grapple saw is significantly slower. On the other hand, the grapple saw will offer the benefits of a lower investment cost, and of a better capacity to handle slash, which is generated in large amounts during whole-tree coppice operations (Spinelli, Magagnotti, Aminti, De Francesco, & Lombardini, 2016).

Grapple saws can be used for other additional tasks than just coarse processing. That is the case of loading and bunching, which has already been described by Ruch et al. (2016) in very clear terms. A grapple saw is the ideal complement to any loading or stacking unit, because it allows reducing load size within the limits allowed by the forwarder bunk or the wood stack, respectively. When working at the stump site, a grapple saw is generally used for pre-bunching manually felled trees, which cannot be oriented and packed as accurately as when felling is performed by a machine. That is one of the reasons why grapple saws are so popular in coppice operations. The difficulty with handling coppice clumps and the need to preserve stump integrity force most operators to adopt motor-manual felling, which prevents accurate bunching (Spinelli, Pari, Aminti, Magagnotti, & Giovannelli, 2017). In this case, it is common practice to detach a small excavator for pre-bunching prior to extraction. If this excavator is fitted with a grapple saw, then bunches can be cut to suitable lengths for forwarder extraction, which minimizes product contamination compared with skidding. Of course, pre-bunching is an additional task and may take a variable length of time depending on how scattered and aligned manually-felled trees are. In turn, that may explain why our study found that work at the stump site was less productive than work at the landing, where trees arrived already in bunches. This difference was not found significant because of excessive variability in the data, which may derive from the variable quality of manual felling, whereby trees were already grouped and aligned in some plots, while scattered and entangled in others.

This study also quantifies the effects of different work organization models. Hot deck operations incur twice the amount of delays as cold deck operations. Such large difference is the result of machine interaction, and is reflected in previous studies about harvester and processor delays (Spinelli & Visser, 2008). Whenever possible, feedstock buffers should be interposed between subsequent tasks within the same production chains. In fact, loaders are often stationed at constrained landings or under yarders in order to remove loads from the chute and place them on stacks. If so, interaction delay is inevitable and must be factored into the planning. Use of a grapple saw would simply improve the capability of the loader already detached for the task, and the additional cost should be considered as a marginal cost, because the loader is already an integral part of the operation.

3.6. CONCLUSIONS

A grapple saw is a relatively inexpensive piece of equipment capable of boosting the capacity of loaders used in forestry. A grapple saw is a good choice when the use of cut-to-lenght processors is not necessary or possible. For this reason, grapple saws are especially popular in energy wood harvesting, where accurate processing to exact size specifications is not required. The same applies to coppice operations, where loaders are often deployed for pre-bunching cut trees after motor-manual felling. Whatever the job, grapple saws allow increasing the mechanization level of small-scale enterprises, with all related benefits in terms of higher productivity and superior work safety.

3.7. ACKNOWLEDGEMENTS

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3.8. REFERENCES

Björheden R (1991) Basic time concepts for international comparisons of time study reports. Int J For Eng 2:33–39. doi: 10.1080/08435243.1991.10702626

Buckley GP (1992) Ecology and management of coppice woodlands. Chapman & Hall, London

Cacot E (2010) La mécanisation de l 'exploitation des peuplements feuillus. Forêt-entreprise 190:18–22.

Chakroun M, Bouvet A, Ruch P, Montagny X (2016) Performance of two shear heads for harvesting biomass in hardwood stands in France. Biomass and Bioenergy 91:227–233. doi: 10.1016/j.biombioe.2016.05.029

Hanzelka NC, Bolding MC, Sullivan J, Barrett SM (2016) Productivity and costs of utilizing small-diameter stems in a biomass-only harvest. Int J For Eng 27:43–52. doi: http://dx.doi.org/10.1080/14942119.2015.1135615

Hédl R, Kopecký M, Komárek J (2010) Half a century of succession in a temperate oakwood: From species-rich community to mesic forest. Divers Distrib 16:267–276. doi: 10.1111/j.1472-4642.2010.00637.x

Jansen P, Kuiper L (2004) Double green energy from traditional coppice stands in the Netherlands. Biomass and Bioenergy 26:401–402. doi: 10.1016/j.biombioe.2003.08.004

Kofman P (1995) Siwork 3: user guide. Danidh Forest and Landscape Research Institute, Vejle, Denmark

Labelle ER, Soucy M, Cyr A, Pelletier G (2016) Effect of Tree Form on the Productivity of a Cut-to-Length Harvester in a Hardwood Dominated Stand. Croat J For Eng 37:175–183.

Laina R, Tolosana E, Ambrosio Y (2013) Productivity and cost of biomass harvesting for energy production in coppice natural stands of Quercus pyrenaica Willd. in central Spain. Biomass and Bioenergy 56:221–229. doi: 10.1016/j.biombioe.2013.04.016

Magagnotti N, Picchi G, Spinelli R (2013) A versatile machine system for salvaging small-scale forest windthrow. Biosyst Eng 115:381–388. doi: 10.1016/j.biosystemseng.2013.05.003

Magagnotti N, Spinelli R (2012) Good practice guidelines for biomass production studies, 1st edn. CNR IVALSA, Sesto Fiorentino, Firenze, Italy

Malinen J, Laitila J, Väätäinen K, Viitamäki K (2016) Variation in age, annual usage and resale price of cut-to-length machinery in different regions of Europe. Int J For Eng 27:95–102.

Matula R, Svátek M, Kůrová J, et al (2012) The sprouting ability of the main tree species in Central European coppices: Implications for coppice restoration. Eur J For Res

131:1501–1511. doi: 10.1007/s10342-012-0618-5

McEwan A, Magagnotti N, Spinelli R (2016) The effects of number of stems per stool on cutting productivity in coppiced Eucalyptus plantations.

Miyata ES (1980) Determining fixed and operating costs of logging equipment. Gen Tech Rep NC-55 1–20.

Nicolescu V-N, Pyttel P, Bartlett D (2015) Evolution and perspectives of coppice forests in European countries and South Africa. Brasov

Olsen ED, Hossain MM, Miller ME (1998) Statistical comparison of methods used in harvesting work studies. Corvallis, OR

Payne RW (2003) General balance, large data sets and extensions to unbalanced treatment structures. Comput Stat Data Anal 44:297–304.

Picchio R, Maesano M, Savelli S, Marchi E (2009) Productivity and Energy Balance in Conversion of a Quercus Cerris L. Coppice Stand into High Forest in Central Italy. Croat J For Eng 30:15–26.

Pottie M, Guimier D (1986) Harvesting and transport of logging residuals and residues. Pointe Claire, QB, Canada

Ruch P, Montagny X, Bouvet A, et al (2016) Mechanized processing of big broadleaved crowns an operational reality. In: 49th FORMEC Symposium. Warsaw, pp 111–117

Schweier J, Spinelli R, Magagnotti N, Becker G (2015) Mechanized coppice harvesting with new small-scale feller-bunchers: Results from harvesting trials with newly manufactured felling heads in Italy. Biomass and Bioenergy 72:85–94. doi: 10.1016/j.biombioe.2014.11.013

Spinelli R, Cacot E, Mihelic M, et al (2016a) Techniques and productivity of coppice harvesting operations in Europe: a meta-analysis of available data. Ann For Sci 73:1125–1139. doi: 10.1007/s13595-016-0578-x

Spinelli R, Cuchet E, Roux P (2007) A new feller-buncher for harvesting energy wood: Results from a European test programme. Biomass and Bioenergy 31:205–210. doi: 10.1016/j.biombioe.2006.08.002

Spinelli R, Magagnotti N, Aminti G, et al (2016b) The effect of harvesting method on biomass retention and operational efficiency in low-value mountain forests. Eur J For Res 135:755–764. doi: 10.1007/s10342-016-0970-y

Spinelli R, Magagnotti N, Picchi G (2010) Deploying Mechanized Cut-to-Length Technology in Italy: Fleet Size, Annual Usage, and Costs. Int J For Eng 21:23–31.

Spinelli R, Magagnotti N, Sperandio G, et al (2011) Cost and Productivity of Harvesting High-Value Hybrid Poplar Plantations in Italy. For Prod J 61:64–70.

Spinelli R, Pari L, Aminti G, et al (2017) Mortality, re-sprouting vigor and physiology of coppice stumps after mechanized cutting. Ann For Sci. doi: 10.1007/s13595-016-0604-

z

Spinelli R, Visser R (2008) Analyzing and estimating delays in harvester operations. Int J For Eng 19:36–41. doi: 10.1080/14942119.2008.10702558

Suchomel C, Becker G, Pyttel P (2011) Fully Mechanized Harvesting in Aged Oak Coppice Stands. For Prod J 61:290–296. doi: 10.13073/0015-7473-61.4.290

Suchomel C, Spinelli R, Magagnotti N (2012) Productivity of processing hardwood from coppice forests. Croat J For Eng 33:39–47.

Tabacchi G, Di Cosmo L, Gasparini P (2011) Aboveground tree volume and phytomass prediction equations for forest species in Italy. Eur J For Res 130:911–934. doi: 10.1007/s10342-011-0481-9

Visser R, Spinelli R (2012) Determining the shape of the productivity function for mechanized felling and felling-processing. J For Res 17:397–402.

Zimbalatti G, Proto AR (2009) Cable logging opportunities for firewood in Calabrian forests. Biosyst Eng 102:63–68. doi: 10.1016/j.biosystemseng.2008.10.008

CHAPTER 4 – The effect of harvesting method on biomass retention and operational efficiency in low-value mountain forests

4.1. ABSTRACT

This study determined the biomass retention effects and the technical–financial performance of alternative harvesting practices, applied to mountain sites. The two alternatives were: whole-tree (WT) and tree-length (TL) harvesting. Five cable yarding sites were selected from a larger pool of available sales, and on each site two adjacent and parallel cable corridors were set up, using the same base equipment and crew. For each of the 10 corridors (i.e. 5 sites × 2 corridors), the following data were recorded: biomass retention, product output, time and fuel inputs. Opting for TL harvesting resulted in a large (66%) and significant increase in biomass retention, which may prove attractive where intensified biomass removal may jeopardize soil fertility and biodiversity. TL harvesting also resulted in a moderate increase (13%) of total harvesting cost. Furthermore, TL harvesting required 30% more labour input than WT, which may represent a disadvantage when forest labour is scarce. The increased labour use in TL harvesting occurs mainly at the stump site, where accident risk is highest. For all these reasons, managers should take their decision very carefully and opt out of more efficient WT harvesting only when the risk derivedfrom increased biomass removal is quite severe.

4.2. INTRODUCTION

Natural forests cover 40% of the Alpine landscape and play an important role in supporting local economy (Onida 2009). Alpine forests accomplish many functions at one time, and therefore they are the object of so-called multi-functional forest management (Brang et al. 2006). In particular, alpine forests have both a productive and a protective function: while producing large amounts of timber, they also prevent soil erosion and shield settlements from avalanches and rock fall (Dorren et al. 2004). The need to guarantee both cost-effective wood production and efficient soil protection makes alpine forestry especially complex. Furthermore, the typical access constraints of the Alpine territory often prevent the introduction of modern harvester-forwarder technology, which is a main solution to cost containment in the face of increasing fuel and labor cost (Spinelli and Magagnotti 2011). As a consequence silvicultural treatment is often delayed and results in a skewed age distribution, because not enough young trees are available for replacing the old ones, as they succumb to age and disease (Binder et al. 2004). Excessive ageing contributes to the high vulnerability of Alpine forests in the face of climate change (Seidl et al. 2011). Therefore, it is crucial to optimize forest operations in order to guarantee timely regeneration and maximize forest resiliency.

When slope gradient exceeds 40%, ground-based harvesting technology cannot offer good results and cable logging is preferable (Bont and Heinimann 2012). Cable yarding is the most common steep slope harvesting technique world wide and it is especially popular in the Alps, where it was originally developed. As a matter of fact, alpine logging companies have a long-standing tradition with yarding. In 2012, there were over 350 cable logging contractors in alpine Italy alone (Spinelli et al. 2013a). On steep terrain, cable yarding is the cost-effective alternative to building an extensive network of skidding trails and results in a much lower site impact compared with ground-based logging (Bolding et al. 2011, Spinelli et al. 2010a). On the other hand, cable yarding is inherently expensive because it is normally deployed on difficult sites. For this reason, cable logging offers lower profit margins compared with ground-based logging (Drews et al. 2001, Spinelli et al. 2015).

Much effort has been applied to increasing the profitability of cable logging operations (Cavalli 2012). Like for most other fields of human activity, mechanization appears as one of the best ways to increase the financial performance of cable-logging operations. In this respect, a most popular solution consists in whole-tree (WT) extraction, which allows increasing the productivity of both extraction and processing (Ghaffariyan et al. 2009). Once the trees are delivered to the landing, processing becomes faster and safer, due to the easier work conditions (Spinelli et al. 2009). What is more, processing can be mechanized by deploying dedicated multi-functional machines (i.e. processors), which cannot normally negotiate steep terrain but can station at the landing and work the trees after extraction. Under these conditions, the introduction of a processor is not overly expensive. A loader is needed at the landing for stacking the trees in any case, and this loader can be used as the base machine for carrying the processor head, so that conversion to mechanized processing may only require the additional investment in a processor head, not in a complete machine (Wang and Haarlaa 2002). Besides, excavator-based processors are more suited than dedicated units to working under a yarder, due to their continuous rotation capacity and to the possibility of installing a dual processor-grapple head (Spinelli et al. 2010b).

Adoption of WT harvesting offers the additional advantage of higher biomass recovery, because tree tops and branches are also moved to the landing, and they can be recovered for use as energy wood, to match the increasing demand generated by the growing bioenergy market (Lundmark 2006, Tyner 2008). In most cases, energy wood production is not the main goal of harvesting, but it represents an additional source of income (Han et al. 2004) or – in the worst case – a cost-effective way for disposing of the residues (Puttock et al. 1995).

However, whole-tree (WT) extraction is coming under increased criticism because of the risk for soil nutrient depletion (Helmisaari et al. 2011), which may result from removing nutrient-rich top and branch material (Lamers et al. 2013). Furthermore, the intensification of biomass removal may alter soil carbon balances (Bucholz et al. 2014) and result in increased GHG emissions (Mika and Keeton 2014). Intensified biomass removal at the time of harvesting may also impact the biodiversity of forest sites (Littlefield and Keeton 2012). However, studies on the long-term effects of WT harvesting are not consistent, and report about negative, positive or non-existent effects, thus hinting at a site-specific dose-response (Wall 2012).

As a compromise solution, trees could be delimbed and topped before extraction, but not merchandised. That would allow reducing inefficient stump-site processing work, while increasing biomass retention to mitigate possible adverse effects (Mika and Keeton 2013). This work procedure is known as tree-length (TL) harvesting and is widely used to avoid the accumulation of residues at space-constrained landings (Westbrook et al. 2007). On the other hand, tree-length harvesting is less efficient than whole-tree harvesting, and may result in higher harvesting costs. However, comparison studies between the two systems are old, do not include cost and biomass retention at the same time and concern use in ground-base logging, not cable-logging (Putnam 1983).

Therefore, the goal of this study was to compare TL and WT harvesting under the conditions of cable yarding, covering biomass retention, labour productivity, energy use, harvesting cost and operation profitability at the same time. The null hypothesis was no significant difference existed between the two methods for any of the abovementioned aspects.

4.3. MATERIALS AND METHODS

A comparative trial was carried out in the Italian Alps, near Lake Como (Fig. 4.1). For the purpose of the study, five cable logging sites were selected from a larger pool of available sales (Tab. 4.1).

Each site represented a separate and homogeneous forest compartment. All sites were characterized by deep brown soil with sandy loam texture, except for site 4 that had a dry, shallow rendzina. The selected sites were meant to represent the main stands available for harvest in the area, and those that are most critical in terms of financial viability and site sensitivity. Young softwood plantations and aged coppice stands require urgent management but offer a low-value harvest, which does not encourage owner action. Under these conditions, mechanization and the additional harvest of biomass products are often considered as ways to increase cost-efficiency and make management more attractive. That is the very reason why such stand types became priority targets for the study.

On each site, two adjacent and parallel cable lines were set up, using the same base equipment and crew. The distance between the centres of the two corridors varied between 30 and 40 m. On one of the paired corridors, TL harvesting was applied: trees were motor-manually felled, topped and coarsely delimbed, then yarded as full length stems, and finally crosscut and stacked at the landing using a chainsaw and an excavator with a grapple-saw. Minimum topping diameter was 10 cm for conifers and 5 cm for hardwoods. On the other corridor, WT harvesting was applied: trees were motor-manually felled, yarded whole and mechanically processed at the landing, using an excavator-base processor (Fig. 4.2).

Paired corridors had approximately the same length and removal intensity, as confirmed by a preliminary timber cruise. In any case, the stand types targeted by this study were very homogenous (even-aged monospecific plantations, or even-aged coppice), with minimum differentiation occurring within the compartments themselves. Corridor length varied between sites, ranging from 150 to 400 m. The mean corridor length was 270 m, with no significant differences between treatments. Product removal varied between 0.3 and 2 m^3 per metre of corridor, with small differences between treatments, but a clear stratification between conifer and broadleaf stands (0.46 and 1.52 m^3 per metre of corridor, respectively; $p = 0.01$).

Fig. 4.1 – Location of the test sites

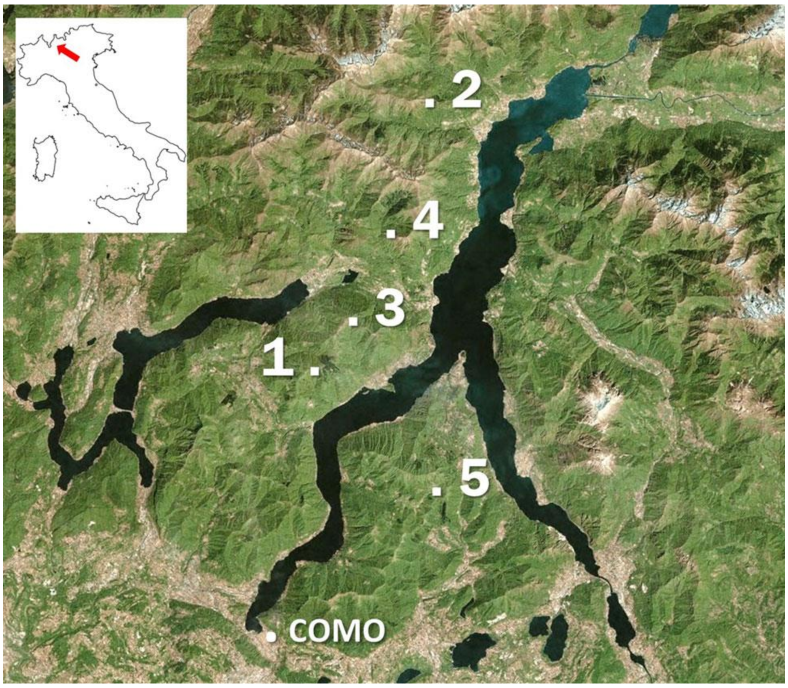


Fig. 4.2 – Typical configuration of a cable yarding operation (site 4, WT)

Different machines and crews worked at different sites, although technology levels were quite similar (Table 4.2). In particular, felling (and the eventual processing) was performed with professional chainsaws in the 60 cm^3 engine displacement class; extraction was performed with medium- sized tower yarders, with a skyline capacity of approximately 600 m (all yarders were set up in a standing skyline configuration); landing work was conducted alternatively with light excavators in the 8-ton class (TL harvesting) or medium-sized excavators in the 18-ton class (WT harvesting), the former equipped with a grapple saw, the latter with a 50-cm capacity roller-type processor. All machines were operated by experienced professionals, who had run them for several years. The skills of study operators were considered representative of the region and were fairly similar between them.

Table 4.1 – Description of the test sites

Site	#	1	2	3	4	5
Placename		Colonno	Gravedona	Ossuccio	Grandola	Lasnigo
Surface	ha	2.00	4.46	4.30	3.96	1.40
Altitude	m a.s.l.	1250	1300	1325	950	800
Slope gradient	%	48	50	42	60	70
Species		Spruce	Spruce	Beech	Beech	Mix h.wood
Management		Plantation	Plantation	Coppice	Coppice	Coppice
Treatment		Gap cut	Gap cut	Selection cut	Selection cut	Selection cut
Age	years	60	51	50	50	30
Stocking	m^3 ha^{-1}	428	173	238	165	156
Stocking	trees ha^{-1}	800	425	785	600	578
Removal	m^3 ha^{-1}	428	67	123	123	78
Removal	trees ha^{-1}	800	251	567	450	382
Harvest intensity	% volume	100	39	52	74	50
Harvest intensity	% trees	100	59	72	75	66
Harvest tree	m^3	0.535	0.268	0.217	0.273	0.204

Notes: spruce = Norway spruce, (*Picea abies* Karst.); Beech = Fagus sylvatica L.;
Mix h.wood = Hornbeam (*Ostrya carpinifolia* Scop.) and Chestnut (*Castanea sativa* L.);
Stocking = pre-harvest inventory.

For each of the 10 corridors (i.e. 5 sites × 2 corridors), the following data were recorded: biomass retention, product output, time and fuel inputs. Each corridor represented one repetition in the experiment, so that each treatment was replicated 5 times.

Biomass retention was determined on ten to fifteen 1 × 1 m sample plots per corridor, using an improved version of the protocol developed by the Australian Forest Operations Research Alliance at the University of the Sunshine Coast (Ghaffariyan et al. 2011). Before locating the plots, the sampled area was divided in two strata according to residual biomass load, in order to increase the accuracy of sampling and reduce the number of needed sample plots. After that, 50 sample plots per corridor were located systematically on the terrain, and each of them was attributed to one of the strata. From the original 50 plots, 20 plots were selected randomly, reflecting the proportion between the strata. All the residue available on each of the 20 selected plots was weighed, separately for its main components, and namely: (a) branches with a large-end diameter >3 cm, (b) branches with a large-end diameter between 1 and 3 cm, and (c) branches with a large-end diameter <1 cm, foliage and cones (the latter for conifers only). The total weight of the biomass found on each plot was entered in a dedicated calculator, which computed the variance for the plots in each stratum. Based on that, the calculator provided the additional number of plots to be sampled, in order to obtain the desired accuracy (15% in this case). Furthermore, five 500-g samples per corridor and component were collected in order to determine moisture content with the gravimetric method, according to European standard CEN/TS 14774-2. That allowed estimating biomass retention as dry mass. Sample plots were located after harvest only, and therefore the estimated biomass loads included the biomass already on the forest floor before harvest.

Product output was determined by accumulating all the biomass extracted from each corridor in separate piles divided by assortment type, and then weighing the wood in each pile on a certified weighbridge (firewood and chips) or scaling it with caliper and measuring tape (timber). In all cases, 5 sample discs were collected from each pile, in order to determine wood density and moisture content - the latter with the gravimetric method, as above.

Time input was determined through time sheets, compiled daily by the foreman. Each daily record contained the hours and minutes worked by each crew member, separately for the following activities: stump-site work, extraction, landing-site work. Stump-site work included felling under the WT treatment, or felling, delimbing and topping under the TL treatment. Landing-site work included delimbing, topping, crosscutting and stacking under the WT treatment, or crosscutting and stacking under the TL treatment. The incidence of delays was determined through work sampling, conducted at random intervals along the study (Spinelli et al. 2013b). Mean load size was calculated by dividing the total amount of wood extracted during the study by the number of turns, as recorded on the time sheets. Fuel input was determined by recording all fuel refills for each machine.

Machine costs were calculated with the harmonized method developed within the scope of European COST Action FP0902 (Ackerman et al. 2014). Data about utilization, maintenance and value recovery were obtained directly from the machine owners, and matched published figures (Spinelli et al. 2011a). These data were used to estimate investment cost and maintenance cost (Table 2), whereas labour, fuel and lubricant cost were obtained directly from the daily time sheets. Product price was obtained from the local forester, and was equal to 55 € m^{-3} of timber, 70 € per fresh tonne of firewood and 32 € per fresh tonne of chipwood, before chipping. After accounting for moisture content (varying between 22 and 42%) and wood density, prices converted into 128, 127 and 64 € per dry tonne, for timber, firewood and chipwood, respectively. These prices were valid for the wood stacked at landing, before transportation to the user plant. Energy use was estimated as the sum of direct and indirect energy inputs. Direct energy inputs were calculated by multiplying the total weight of chainsaw fuel, diesel and lubricants by 55.3, 51.5 and 83.7 MJ kg^{-1} respectively (Spinelli and Magagnotti 2011). The indirect consumption represented by machine manufacturing, repair and maintenance was estimated as 30% of direct energy use (Mikkola and Ahokas 2010). The energy input derived from manual labour was estimated at 1.8 MJ h^{-1} (Christie 2008). Energy output was estimated as 19 and 20 MJ per kg of dry matter for broadleaf and conifer trees, respectively (Spinelli et al. 2011b). Data were analysed with the Statview advanced statistics software (SAS 1999). Differences between treatments (i.e. harvesting methods) were tested with the Wilcoxon signed rank test, which is a robust nonparametric test designed for conducting paired comparisons when the distribution of data does not meet the normality assumption. However, the per cent distribution data for the logging residue components (i.e. branches >3 cm, branches 1–3 cm etc.) were normalized using the logit transformation and then tested with a standard analysis of variance for checking the significance of any differences between treatments, as indicated by the interaction factor ‘‘component × treatment’’ (Eliasson et al. 2015). A different and simpler approach was adopted for the distribution of different product assortments. In that case, the significance of any differences between the distributions recorded for different methods at the same sites was tested with the Pearson’s Chi-Square (χ^2) test. In all analyses, the elected significance level was $\alpha<0.05$. Overall, the test covered 16.12 ha, which yielded 1075 tonnes of dry wood. Harvesting such a large amount of biomass required 2793 man hours, 3172 L of diesel fuel and 329 L of petrol mix. Work sampling sessions covered a total of 106 worksite hours.

Table 4.2 - Machinery used for the tests and estimated machine cost figures

Site	#	All	1	2, 4	3, 5	All TL	All WT
Machine	Type	Chainsaw	Yarder	Yarder	Yarder	Excavator	Excavator
	Make	Husqvarna	Greifenberg	Valentini	Konrad	Komatsu	Liebherr
	Model	562 XP	TG700	V600/1000	Endmast	PC75	A900C
	Carriage	-	CRG15	HSK2002	Woodliner	-	-
Attachment	Type	-	-	-	-	Grapple saw	Processor
	Make	-	-	-	-	Hultdins	Konrad
	Model	-	-	-	-	Supersaw	Woody 50
Investment	€	1,000	150,000	300,000	160,000	90,000	220,000
Resale (20%)	€	200	30,000	60,000	32,000	18,000	44,000
Service life	Years	2	10	10	10	10	10
Utilization	h year^{-1}	800	800	800	800	800	800
Interest rate	%	4	4	4	4	4	4
Depreciation	€ year^{-1}	400	12,000	24,000	12,800	7,200	17,600
Interests	€ year^{-1}	32	3,840	7,680	4,096	2,304	5,632
Insurance	€ year^{-1}	32	3,840	7,680	,4096	2,304	5,632
Fuel	€ odt^{-1}	Estimated case by case based on the results in Table 3					
Lube	€ odt^{-1}	10% of fuel cost					
Repairs	€ year^{-1}	400	6,000	12,000	6,400	3,600	8,800
Labour	€ odt^{-1}	Estimated case by case based on the results in Table 3					
Total	€ year^{-1}	864	25,680	51,360	27,392	15,408	37,664
Total	€ h^{-1}	1.1	32.1	64.2	34.2	19.3	47.1

Notes: the total cost in this table refers to investment and maintenance only, and it does not include fuel, lubricants, labour and 25 % overheads

4.4. RESULTS

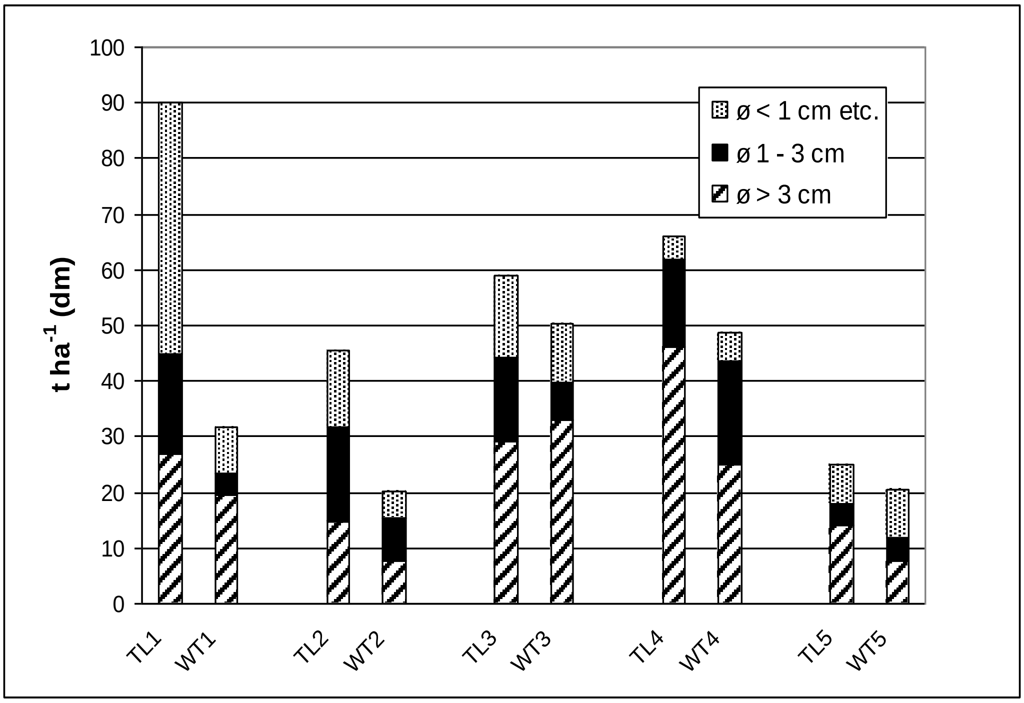
Post-harvest biomass retention varied between 20 and 90 tonnes of dry matter per hectare, depending on site and treatment (Fig. 4.3). There were no differences between conifer and broadleaf sites. In contrast, there was a clear stratification between sites with lower removals (i.e. sites 2 and 5) and sites with larger removals (i.e. sites 1, 3 and 4), and between harvest methods. As an average, adoption of the TL method resulted in a 66% increase in biomass retention. To say it another way, WT harvesting removed 40% of the residues that would be left on site if the TL method had been adopted. This difference was significant for $p = 0.04$. Of course, the exact differences between the two methods varied with stand type and were lower in broadleaf stands, where topping diameter was smaller because large branches were converted into firewood. In those cases, large branches were left attached to the stem and taken to the landing, regardless of harvesting method.

On an average, half of the residue mass left on site consisted of branches with a butt diameter larger than 3 cm. The rest was equally distributed between branches with a diameter between 1 and 3 cm, and smaller branches, foliage and cones. The component breakdown of harvesting residues differed remarkably between sites, but no significant trends could be detected. Harvesting method had no effect on component breakdown (DF = 30, ANOVA $p > 0.05$).

Biomass retention trends were mirrored by biomass removals that were significantly lower for TL harvesting, compared with WT harvesting (Table 4.3). WT harvesting allowed an average increase in biomass recovery of 23%, and this difference was statistically significant ($p = 0.04$). Product characteristics varied with stand type. Both conifer stands yielded a variable mix of timber and wood chips, the latter representing always more than 50% of the total harvest (Figure 4.4). Contrary to expectations, the proportion of timber was higher under the WT treatment, but this trend was deprived of statistical significance ($n = 30$, $\chi^2 = 3.309$, $p = 0.07$). Firewood represented between 75 and 100% of the harvest obtained from hardwood stands. The rest consisted of wood chips. No timber was obtained from these stands, and harvesting method choice had no visible effect on product breakdown.

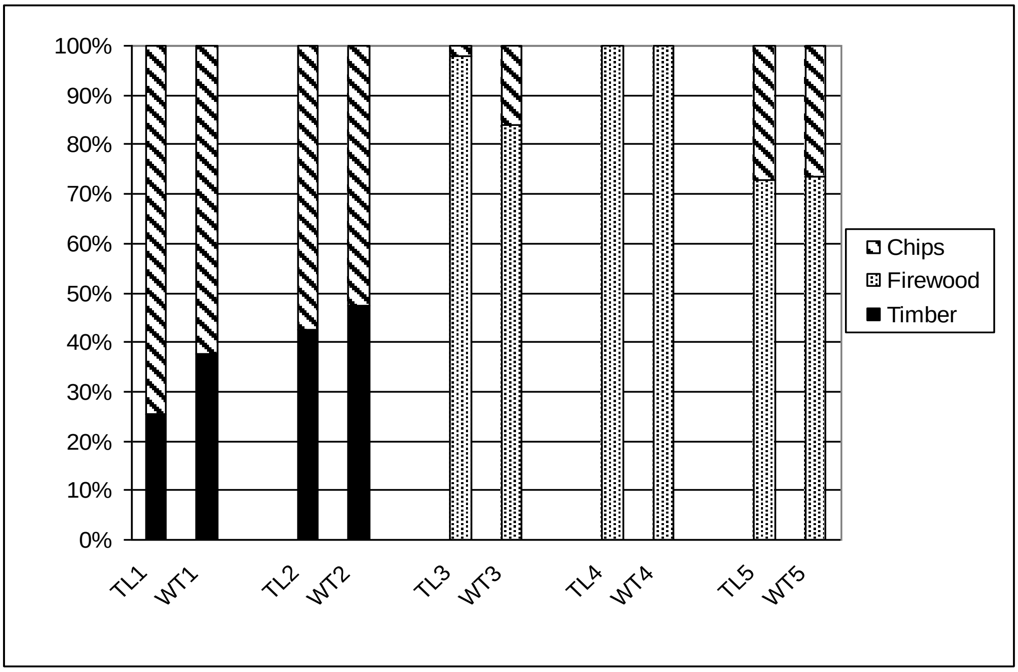
Total time consumption varied between 1.51 and 3.58 worker hours per dry tonne (Figure 4.5). Mean values were 2.27 and 2.98 worker hours per tonne dry matter for WT and TL harvesting, respectively.

Fig. 4.3 - Biomass retention by site, harvesting method and biomass component



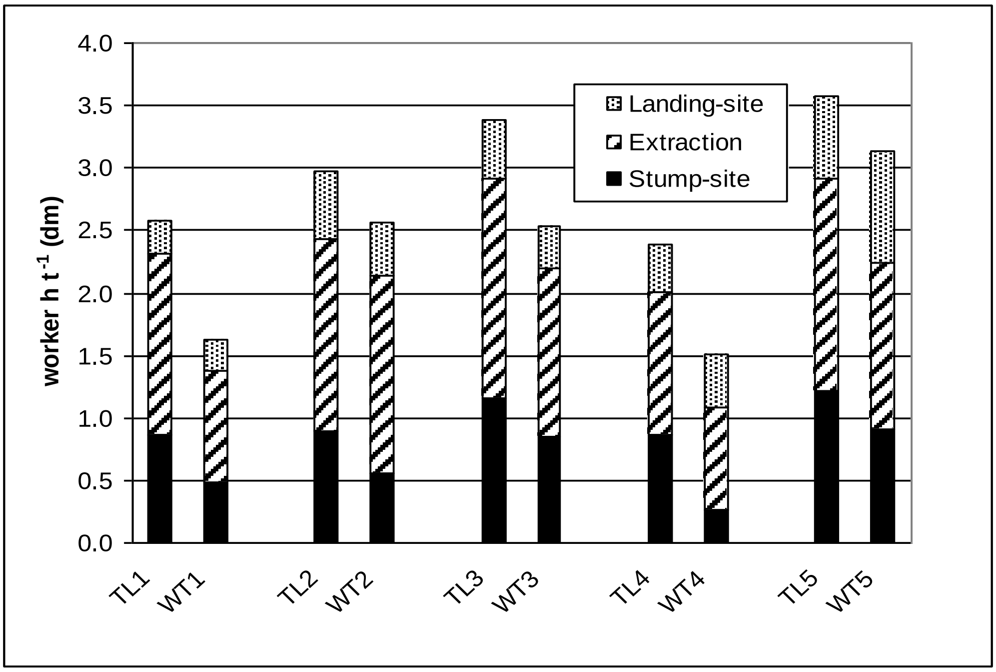
Note: the X axis reports harvesting type and site number (i.e. TL1 = tree length, site 1; WT1 = whole tree, site 1; TL2 = tree length, site 2 etc.); Ø = butt diameter; dm = dry matter

Fig. 4.4 - Product assortment breakdown by site and harvesting method.



Note: the X axis reports harvesting type and site number (i.e. TL1 = tree length, site 1; WT1 = whole tree, site 1; TL2 = tree length, site 2 etc.)

Fig. 4.5 - Time consumption per unit product by site, harvesting method and activity



Note: the X axis reports harvesting type and site number (i.e. TL1 = tree length, site 1; WT1 = whole tree, site 1; TL2 = tree length, site 2 etc.); dm = dry matter

Therefore, shifting from WT harvesting to TL harvesting resulted in an average increase in total time consumption of 31%, and this difference was statistically significant (Table 4.3). In particular, TL harvesting required 63% more stump-site work, 27% more extraction work and 1% less landing-site work, compared with WT harvesting. However, only the stumpsite work time difference was statistically significant. In contrast, the recorded extraction time difference can be suggestive of the higher extraction efficiency of WT harvesting, but offers no conclusive evidence for it. In any case, extraction was the most time-consuming activity, requiring between 42 and 62% of the total work time per unit product. Yarder set up and dismantle took between 11 and 26% (mean = 20%) of total extraction time, with no clear differences between treatments. Yarder load varied from 0.3 to 0.6 tonnes dry matter per turn and was 30% larger for the WT treatment. This difference was statistically significant (Table 4.2).

Fuel use was higher for TL harvesting compared to WT harvesting, but the difference was statistically significant for petrol mix (i.e. chainsaw fuel) only, not for diesel fuel. TL harvesting showed a significantly higher energy consumption (+14 %) per unit product and a significantly less favourable energy balance (-20%), compared with WT harvesting. In both cases, the energy output–input ratio was very high and larger than 100 (Table 4.3).

Total harvesting cost varied from 55 to 140 € t^{-1} dry matter (Fig. 4.6), with large variations between sites and treatments. Average harvesting cost was 94 and 106 € t^{-1} dry matter for WT and TL harvesting, respectively (Table 4.3). Favouring TL over WT harvesting incurred a 13% cost increase, but the difference lacked statistical significance. This may derive from the confounding effect of the test conducted at Site 5, where WT harvesting did result in a higher cost compared with TL harvesting. In any case, fuel cost represented a very small proportion of total cost, varying from 3 to 6%. As an average, capital cost represented 44 and 5% of TL and WT harvesting cost, respectively. Conversely, labour cost represented 52 and 45% of TL and WT harvesting cost, respectively. These differences between harvesting methods were statistically significant.

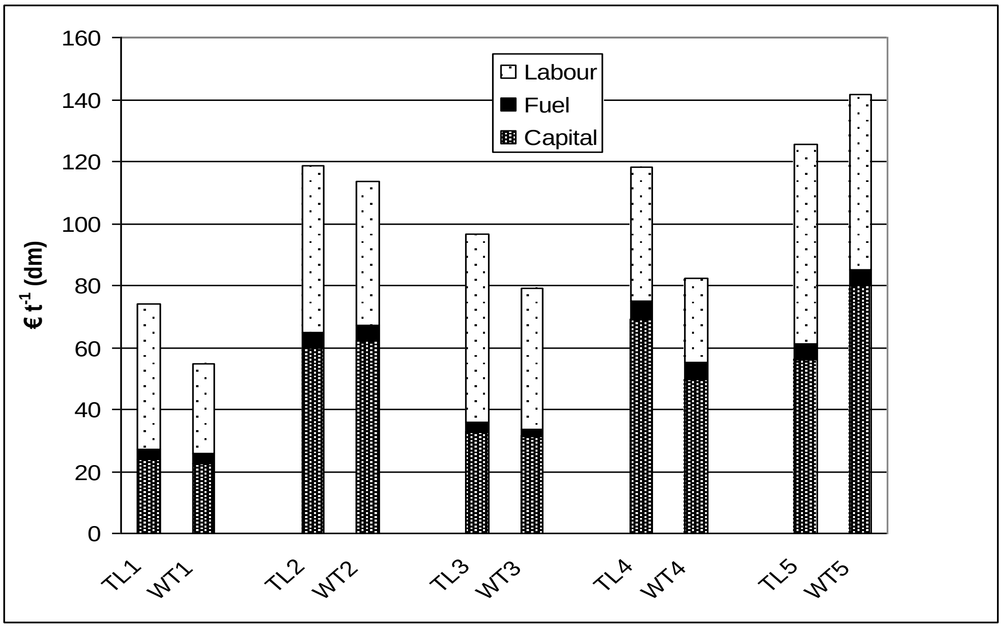
Harvesting revenues varied between 80 and 127 € t^{-1} dry matter, with an average value of 107 € t^{-1} dry matter (Table 4.3). Profits ranged from -40 to 41 € per dry tonne (Fig. 4.7). Losses were incurred on the two sites with the smallest removals (i.e. sites 2 and 5). Harvesting method had a no impact on revenues and a relatively small impact on profits. In neither case was the effect of harvesting method significant.

4.5. DISCUSSION

Many papers already contain detailed figures for biomass retention under different operational scenarios (Thiffault et al. 2014; Kizha and Han 2015). However, very few of them offer comprehensive information about the effect of variable retention levels on operational planning and financial viability. This study fills the gap by determining both the biomass retention effects and the financial performance of alternative harvesting practices. In essence, it attaches a price tag to increased biomass retention, which is essential to making informed management decisions. To our knowledge, no paper has yet produced such information for mountain operations, where profit margins are especially thin.

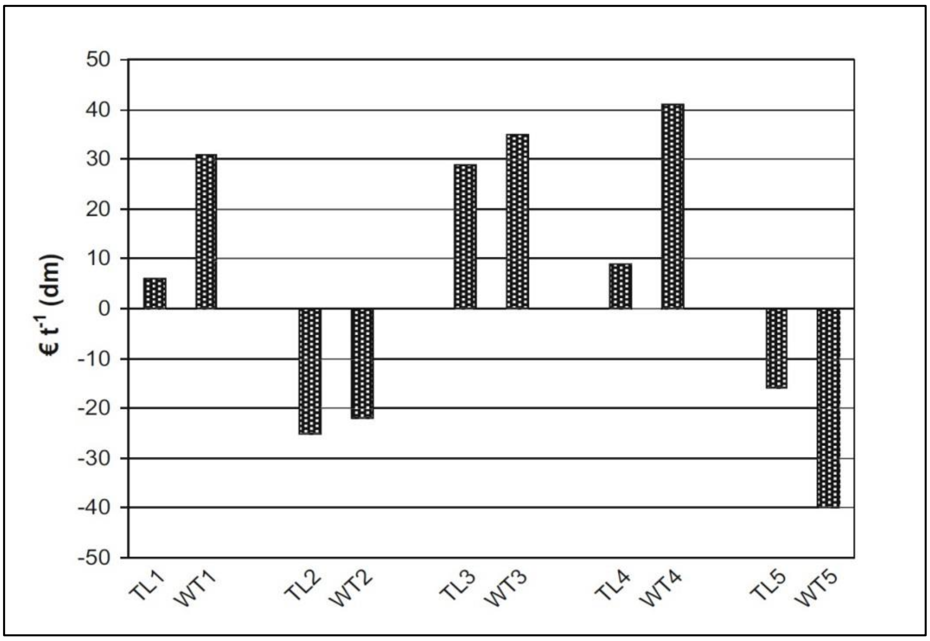
The residue loads reported in this study are compatible with those reported in previous studies, which vary from 4 (Hytönen and Moilanen 2014) to 140 (Cormier et al. 2012) t ha^{-1} dry matter.

Fig. 4.6 - Total harvesting cost per unit product by site, harvesting method and production factor.



Note: the X axis reports harvesting type and site number (i.e. TL1 = tree length, site 1; WT1 = whole tree, site 1; TL2 = tree length, site 2 etc.); dm = dry matter

Fig. 4.7 - Harvesting profit by site and harvesting method.



Note: the X axis reports harvesting type and site number (i.e. TL1 = tree length, site 1; WT1 = whole tree, site 1; TL2 = tree length, site 2 etc.); dm = dry matter

Table 4.3 - Comparison between TL and WT harvesting: summary data (n = 10)

		Mean			Median			WSR
		TL	WT	Δ(%)	TL	WT	Δ(%)	*p* value
Removal	t (dm) corridor^{-1}	96.5	118.5	-19	91.4	121.7	-25	**0.04**
Corridor length	m	261	280	-7	275	250	10	>0.99
Stump-site work	Worker hours t^{-1} (dm)	0.999	0.613	63	0.896	0.552	62	**0.04**
Extraction work	Worker hours t^{-1} (dm)	1.517	1.194	27	1.536	1.331	15	0.08
Landing work	Worker hours t^{-1} (dm)	0.464	0.468	-1	0.456	0.421	8	0.89
Total work	Worker hours t^{-1} (dm)	2.980	2.274	31	2.971	2.534	17	**0.04**
Petrol mix	L t^{-1} (dm)	0.373	0.244	53	0.362	0.244	48	**0.04**
Diesel	L t^{-1} (dm)	3.040	2.753	10	3.485	3.429	2	0.14
Yarder load	t (dm) turn^{-1}	0.380	0.549	-31	0.380	0.569	-36	**0.04**
Energy cost	Mj t^{-1} (dm)	209.2	183.6	14	231.3	222.5	4	**0.04**
Energy balance	Output input^{-1}	105.4	131.0	-20	82.1	85.4	-4	**0.04**
Harvesting cost	€ t^{-1} (dm)	106.5	94.2	13	118.0	82.3	43	0.14
Product value	€ t^{-1} (dm)	107.4	107.8	0	110.0	110.5	0	0.50
Profit	€ t^{-1} (dm)	0.9	13.6	-93	6.5	30.8	-79	0.35

Note: Wilcoxon signed rank test for the null hypothesis of no difference between TL and WT (null hypothesis is rejected if $p<0.05$); dm = dry matter; TL = tree-length harvesting; WT = whole-tree harvesting; Δ = increment of TL over WT; WSR p value obtained from the nonparametric; Bold italic indicates statistically significant values i.e. $p<0.05$

The data in this study are most often within the 20–50 t ha^{-1} dry matter range, where the majority of the bibliography data tend to group as well (Thiffault et al. 2014). The very high residue loads recorded at Site 1 match those recorded for similar fast-growing conifer plantations established with spruce or pine, which amounted to 170 t ha^{-1} (Cuchet et al. 2004) and 238 t ha^{-1} (Smethhurst and Nambiar 1990), respectively. Assuming a moisture content of 50%, these figures would convert to 85 t ha^{-1} dry matter for spruce and 119 t ha^{-1} dry matter for pine, which are very near to the 90 t ha^{-1} dry matter recorded at Site 1 for spruce.

Unfortunately, the boundary between paired corridors was difficult to identify with certainty at the end of the harvest, as already happened in previous similar studies (Kizha and Han 2015). For this reason, it was decided not to include the exact surface covered by each treatment in the data collection, because small errors might have been magnified during data processing, leading to uncertain results. As a consequence, differences in biomass retention could not be matched exactly with differences in removals, although the study findings are quite consistent, as they indicate increased retention where removals were lighter.

In that regard, the only apparent inconsistency is conifer product breakdown. One would expect the adoption of WT harvesting to shift the product mix towards an increased proportion of chips, as additional branch material is recovered from the site (Spinelli et al. 2014). In fact, the contrary occurred: relative timber yield increased when WT harvesting was applied. That was observed systematically on both conifer sites, which makes coincidence unlikely. The logical explanation is the better value recovery normally achieved with improved work conditions (Murphy et al. 2014). Under the TL harvesting treatment, trees were topped at the stump site, under unfavourable conditions that could motivate quick and imprecise work. In contrast, WT harvesting moved these activities to the landing, where improved job quality would derive from better work conditions and closer supervision (Chung et al. 2014). Of course, salvaging timber material from the chip wood pile may cause a reduction of chip quality and price, which may reflect on total revenue (Spinelli and Magagnotti 2010). However, price effects were not investigated in the study. At any rate, it is unlikely that eventual reductions in chip price may completely offset the value gains obtained from recovering additional timber products, for as low as their grade might be.

It is no surprise that the less mechanized TL harvesting resulted in a higher labour input per unit product. Here, all indicators were consistent: higher time consumption for stump-site work that becomes more complex; lower load size, as a result of trimming out part of the tree before extraction; possibly lower extraction productivity, which is consistent with the lower load size (although this result is not conclusive); significant increase in total time consumption per unit product, deriving from all the above. Previous studies have indicated that opting out of WT harvesting has the very same consequences, which corroborates our results (Adebayo et al. 2007; Bisson et al. 2013). Decreased work efficiency leads to a harvesting cost increase, which the study quantified at 13% or 12 € t^{-1} dry matter. Unfortunately, this difference did not pass the assumed significance level, and therefore such information must be considered suggestive, rather than conclusive. However, all indicators point in the same direction and a previous study offers strong corroboration by indicating a very similar harvesting cost increase (12%) when shifting from WT to TL harvesting in ground-based operations (Putnam 1983). As a matter of fact, the eventual cost increase is relatively small and it may have struggled to emerge over the background noise generated by a study that was conducted under a wide variety of conditions. The relatively small cost gap between the two methods hints at similar variations in capital and labour costs, where the lower labour cost incurred by WT harvesting is almost completely offset by increased capital cost. In that regard, readers must be aware that the TL harvesting as applied in this study was already mechanized through the introduction of a grapple saw, and therefore the study was not comparing a fully mechanized system with a fully motor-manual one. In contrast, the goal was to check the performance of two state-of-the-art systems, each designed to achieve a different goal, i.e. increasing biomass retention or minimizing harvesting cost.

Similar considerations can be made for the revenues and the profits recorded in the study. These were quite variable and two operations actually incurred losses. Except for Site 5, WT harvesting performed better than TL harvesting, but it offered incremental benefits only, and could not change the main trend. It seems that the main drivers of operation profitability are others. This study suggests that removal is a stronger driver than harvesting method, which would be consistent with a harvesting technique (cable yarding) that is especially sensitive to removal intensity.

4.6. CONCLUSIONS

Under the conditions of cable-operations, opting for TL harvesting over WT harvesting allows a large and significant increase in biomass retention, which may prove attractive where intensified biomass removal may jeopardize soil fertility and biodiversity. If properly applied, TL harvesting is likely to result in a moderate increase of total harvesting cost. However, the profit margins of cable operations are quite small, and reducing them may drive management outside the limits of financial viability. Furthermore, TL harvesting requires 30% more labour input than WT. That will make it especially attractive where employment opportunities are scarce, even if the sad reality of industrialized countries is that forest labour is scarce and local entrepreneurs generally need to increase the productivity of the little labour they have available, not reduce it (Allred 2009, Goldstein et al. 2005). Finally, it is worth noticing that the increased labour use in TL harvesting occurs mainly at the stump site, where accident risk is highest (Potočnik et al. 2009). For all these reasons, managers should take their decision very carefully. Ultimately, this study is about a management choice and its consequences: it offers managers solid elements to base their decisions, but these decisions will have to be made case by case depending on the specific conditions encountered at the time.

4.7. ACKNOWLEDGEMENTS

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4.8. REFERENCES

Ackerman, P., Belbø, H., Eliasson, L., De Jong, A., Lazdins, A., Lyons, J., 2014. The COST model for calculation of forest operations cost. Int. J. For. Eng. 25, 75-81.

Adebayo, A., Han, H., Johnson, L., 2007. Productivity and cost of cut-to-length and whole-tree harvesting in a mixed-conifer stand. For. Prod. J. 57, 59-69.

Allred, S., 2009. Logging firm succession and retention. For. Prod. J. 59, 31-36.

Binder, C., Hofer, C., Wiek, A., Scholz, R., 2004. Transition towards improved regional wood flows by integrating material flux analysis and agent analysis: the case of Appenzell Ausserrhoden, Switzerland. Ecol. Econ. 49, 1–17.

Bisson, J., Han, S., Han, H., Zhang, J., Montgomery, T., 2013. Comparing whole tree to tree-length fuel reduction thinning operations: cost and actual amounts of biomass removal. Proceedings of the 36th Annual meeting of the Council on Forest Engineering, Missoula, Montana, USA.

Bolding, C., Aust, W., 2011. Potential Soil Erosion following Skyline Yarding versus Tracked Skidding on Bladed Skid Trails in the Appalachian Region of Virginia. South. J. Appl. For. 35, 131-135.

Bont, L., Heinimann, H., 2012. Optimum geometric layout of a single cable road. Eur. J. For. Res. 131, 1439–1448.

Brang, P., Schönenberger, W., Frehner, M., Schwitter, R., Thormann, J., Wasser, B., 2006. Management of protection forests in the European Alps: an overview. For. Snow Landsc. Res. 80, 23–44.

Buchholz, T., Friedland, A., Hornig, C., Keeton, W., Zanchi, G., Nunery, J., 2014. Mineral soil carbon fluxes in forests and implications for carbon balance assessments. GCB Bioenerg 6, 305–311.

Cavalli, R., 2012. Prospects of research on cable logging in forest engineering community. Croat. J. For. Eng. 33, 339-356.

Christie, C., 2008. Relationship between energy intake and expenditure during harvesting tasks. Occup. Ergon. 8, 1-10.

Chung, W., Venn, T., Loeffler, D., Jones, G., Han, H., Calkin, D. 2014. Assessing the potential for log sort yards to improve financial viability of forest restoration treatments. For. Sci. 58, 641-651.

Cormier, D., Volpé, S., Spencer, S. 2012. Biomass availability related to operational constraints (In French). In: Presentation at the Démo International Conference, Quebec City, Canada, September, 2012. Available at: http:// www.oifq.com/pdf/congres/congres-2012/presentations/cormier.pdf.

Cuchet, E., Roux, P., Spinelli, R. 2004. Performance of a logging residue bundler in the temperate forests of France. Biomass Bioenerg. 27, 31–39.

Dorren, L., Berger, F., Imeson, A., Maier, B., Rey, F., 2004. Integrity, stability and management of protection forests in the European Alps. For. Ecol. Manage. 195, 165–176.

Drews, E., Hartsough, B., Doyal, J., Kellogg, L. 2001. Harvester-forwarder and harvester-yarder systems for fuel reduction treatments. Int J For Eng 12, 81-91.

Eliasson, L., Von Hofsten, H., Johannesson, T., Spinelli, R., Tierfelder, T., 2015. Effects of sieve size on chipper productivity, fuel consumption and chip size distribution for open drum chippers. Croat. J. For. Eng. 36, 11-17.

Ghaffariyan, M., Stampfer K., Sessions J., 2009. Production equations for tower yarders in Austria. Int. J. For. Eng. 20, 17-21.

Goldstein, J., Irland, L., Senick, J., Bassett, E., 2005. The intergenerational supply of loggers under conditions of declining economic well-being. Ind. Relations 44, 331-340.

Han, H., Lee, H., Johnson, L. 2004. Economic feasibility of an integrated harvesting system for small-diameter trees in southwest Idaho. For. Prod. J. 54, 21–27.

Helmisaari, H., Hanssen, K, Jacobson S, Kukkola M, Luiro J, Saarsalmi A, et al., 2011. Logging residue removal after thinning in Nordic boreal forests: Long-term impact on tree growth. For. Ecol. Manage. 261, 1919-1927.

Hytönen, J., Moilanen, M., 2014. Effect of harvesting method on the amount of logging residues in the thinning of Scots pine stands. Biomass Bioenerg 67, 347-353.

Lamers, P., Thiffault, E., Paré, D., Junginger, M., 2013 Feedstock specific environmental risk levels related to biomass extraction for energy from boreal and temperate forests. Biomass Bioenerg 55, 212–226.

Littlefield, C., Keeton, W., 2012. Bioenergy harvesting impacts on ecologically important stand structure and habitat characteristics. Ecol. Appl. 22, 1892–1909.

Lundmark, R., 2006. Cost structure and competition for forest-based biomass. Scand. J. For. Res. 21, 271-280.

Mika, A., Keeton, W., 2014. Net carbon fluxes at stand and landscape scales from wood bioenergy harvests in the US Northeast. GCB Bioenerg. doi: 10.1111/gcbb.12143.

Mika, A., Keeton, W., 2013. Factors contributing to carbon fluxes from bioenergy harvests in the U.S. Northeast: an analysis using field data. GCB Bioenerg. 5, 290–305.

Mikkola, H., Ahokas, J., 2010 Indirect energy input of agricultural machinery in bioenergy production. Ren. En. 35, 23-28.

Murphy, G., Marshall, H., Dick, A., 2014. Time of day impacts on machine productivity and value recovery in an off-forest central processing yard. New Zeal. J. For. Sci. 44, 19.

Onida, M., 2009. The Alps: eight countries, a single territory. Permanent Secretariate of the Alpine Convention. Innsbruck (Austria), 89 p.

Potočnik, I., Pentek, T., Poje, A., 2009. Severity analysis of accidents in forest operations. Croat. J. For. Eng. 30, 171-184.

Putnam, N. 1983. A comparison of productivity for whole tree, tree length, and log length skyline thinning in 35 year old Douglas-fir stands of western Oregon. Master Thesis. Oregon State University, Corvallis, OR. 113 p.

Puttock, D., 1995. Estimating cost for integrated harvesting and related forest management activities. Biomass Bioenerg 8, 73–79.

SAS Institute Inc., 1999. StatView Reference. SAS Publishing, Cary, NC. ISBN-1-58025-162-5. pp. 84-93.

Seidl, R., Rammer, W., Lexer, M., 2011. Climate change vulnerability of sustainable forest management in the Eastern Alps. Clim. Chang. 106, 225–254.

Smethhurst, P., Nambiar, E., 1990. Distribution of carbon and nutrients and fluxes of mineral nitrogen after clearfelling a Pinus radiata plantation. Can. J. For. Res. 20, 1490- 1497.

Spinelli, R., Magagnotti, N., 2011. The effects of introducing modern technology on the financial, labour and energy performance of forest operations in the Italian Alps. For. Pol. Econ. 13, 520–524.

Spinelli, R., Magagnotti, N., 2010. Comparison of two harvesting systems for the production of forest biomass from the thinning of Picea abies plantations, Scand. J. For. Res. 25, 69-77.

Spinelli, R., Visser, R., Thees, O., Sauter, U., Krajnc, N., Riond, C., Magagnotti, N. 2015. Cable logging contract rates in the Alps: the effect of regional variability and technical constraints. Croat. J. For. Eng. 36, 179-187.

Spinelli, R., Lombardini, C., Magagnotti, N. 2014. The effect of mechanization level and harvesting system on the thinning cost of Mediterranean softwood plantations. Silva Fenn. vol. 48 no. 1 article id 1003. 15 p.

Spinelli, R., Magagnotti, N., Facchinetti, D., 2013a: A survey of logging enterprises in the Italian Alps: firm size and type, annual production, total workforce and machine fleet. Int. J. For. Eng. 24: 109–120.

Spinelli, R., Laina-Relaño, R., Magagnotti, N., Tolosana, E., 2013b. Determining observer and method effect on the accuracy of elemental time studies in forest operations. Baltic For. 19, 301-306.

Spinelli, R., Magagnotti, N., Picchi, G., 2011a. Annual use, economic life and residual value of cut-to-lenght harvesting machines. J. For. Econ. 17, 378-387.

Spinelli, R., Nati, C., Sozzi, L., Magagnotti, N., Picchi, G., 2011b. Physical characterization of commercial woodchips on the Italian Energy market. Fuel 90, 2198-2202.

Spinelli, R., Magagnotti, N., Nati, C., 2010a. Benchmarking the impact of traditional small-scale logging systems used in Mediterranean forestry. For. Ecol. Manage. 260, 1997–2001.

Spinelli, R., Magagnotti, N., Picchi, G. 2010b. Deploying Mechanized Cut-to-Length Technology in Italy: Fleet Size, Annual Usage, and Costs. Int. J. For. Eng. 21, 23-31.

Spinelli, R., Magagnotti, N., Nati, C., 2009. Options for the mechanized processing of hardwood trees in Mediterranean forests. Int. J. For. Eng. 20, 39-44.

Thiffault, E., Béchard, A., Paré, D., Allen, D., 2014 Recovery rate of harvest residues for bioenergy in boreal and temperate forests: A review. WIREs Energy Environ. doi: 10.1002/wene.157.

Tyner, W., 2008. The US Ethanol and Biofuels Boom: Its Origins, Current Status, and Future Prospects. BioSci. 58, 646-653.

Wall, A., 2012. Risk analysis of effects of whole-tree harvesting on site productivity. For. Ecol. Manage. 282: 175-184.

Wang, J., Haarlaa, R., 2002. Production analysis of an excavator-based harvester: a case study in Finnish forest operations. For. Prod. J. 52, 85-90.

Westbrook, M., Greene, D., Izlar, R., 2007. Utilizing forest biomass by adding a small chipper to a tree-length southern pine harvesting operation. South. J. Appl. For. 31, 165-169.

CHAPTER 5 - Conclusions

A modern forest management should be focused to ensure the continuous production of multiple products and services that forests can provide to society. Forest operations may play a crucial role in preserving an active forest management, since those can represent a fundamental instrument for forest managers but also an action incentive from a bottom-up perspective. To make it possible, optimize and make economically and environmentally sustainable forest operations is necessary. This thesis focused on coppice forests harvesting analysing the performance of mechanized felling, processing and extraction phases respectively.

Starting from the first harvesting phase, the effect of mechanized felling on mortality and re-sprouting of coppice stumps was inspected. Results showed that mechanized cutting caused a higher stump damage level compared to manual cutting. In particular, shear heads caused a higher proportion of damaged stumps and a larger cutting height. However, measured stump mortality was low and not significantly different from manual cutting. Moreover, mechanized felling did not seem to have any effect on stand regeneration and growth. Such consideration is supported both by sprouts dimensions and stump nutrient content. The technical and economical performances of coppice mechanized cutting using low-cost excavator based equipment were previously studied. This work started to assess the complex issue of coppice regeneration under different mechanized harvesting conditions. Of course, this is the result from the first growing season, further studies will be necessaries to determine if this trend will continue in the following years. To develop this research similar experiences could be conducted focusing on other tree species and/or other climatic conditions. Additionally, such analysis could integrate soil disturbance and ecological aspects. Mechanized felling may influence differently the regeneration of both herbaceous and arboreal stand, altering in the long term the species composition, and then, the resilience of forest ecosystems to climatic and environmental modifications.

Regarding processing phases, another low-cost machinery was evaluated with the aim of improving natural coppice harvesting, that is mainly attributable to small-scale forestry. However, in this case, the knowledge gap was represented by a benchmark about employment, production and cost-efficiency performances. Grapple-saw machines have proved to be widely diffuse in Italy due to low investment cost and high adaptability to different stand and work conditions. Such differences determined a high variability in terms of processing productivity.

This parameter was strongly impacted by individual tree size, work site, work organization and processing quality. In particular, productivity was higher for landing site work, cold deck operations and coarse processing into tree sections. Furthermore, regression analysis showed how productivity grew with piece size until reaching optimum tree mass, then declined.

Those results suggested that grapple saw is suitable to processing material derived from coppice forests. Nevertheless this piece of equipment was economically competitive when the use of cut-to-length processors is not necessary or possible, that is for energy wood production. A key factor affecting grapple saw performance was work organization, such result suggested once more the fundamental role of forest operations planning. Additional studies should be carried out focusing on specific stand, work conditions and machine model with the aim of providing even more conclusive data that can help forest managers and logging companies to opt for the best work configuration.

Concerning mountain regions, forests have also an important role of soil protection. Taking into account all forest operations, the last study analysed the technical and financial performances of two alternative harvesting methods, together with the biomass retention effects. Particular emphasis was put on extraction phases under the conditions of cable yarding. TL harvesting resulted in a considerable increasing in biomass retention, which may prove attractive where repeated biomass removal may endanger soil fertility and biodiversity. However, TL harvesting required more labour input than WT harvesting and caused a moderate enhancing in terms of total harvesting costs. The increased labour use occurs mainly at the stump site, where accident risk is higher. Moreover, TL method showed a higher energy consumption per unit product and a less favourable energy balance, compared to WT harvesting.

For all this reasons, managers should take their decision very carefully, opting for TL harvesting only when the risk derived from intensified biomass removal is quite severe. Further development of this research could be to create some permanent plot where comparing the two methods including soil nutrient and microbial populations analysis, so that to extend the evaluation at ecosystem scale.

The central idea of this thesis was to assess and support a higher level of mechanization in coppice forests harvesting aimed to enhance operator safety and economical sustainability of forest operations.

Thanks to this thesis, several aspects were investigated promoting a multidisciplinary approach to forest operation management, and several new concepts for further studies regarding analysed topics emerged.

In conclusion, an integrated approach to forest management is desirable, encouraging collaboration between different research fields, and dealing with forestry as a complex system. Additionally, even more ambitious results could be achieved establishing deep collaborations between research, forest owner, forest administration and business spheres. In other words, involving all the stakeholders to define common objectives and strategies to maximize products and services provided by forests to the society.