3 Utilisation

Getting down to business.

What products can be produced?

How are the different types of coppice harvested?

What are the impacts of different harvesting methods on soil?

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Coppice products

Guidelines for coppice utilization

Impacts on soil relating to coppice harvesting operations

Coppice Products

Natascia Magagnotti, Janine Schweier, Raffaele Spinelli, Eduardo Tolosana, Paula Jylhä,
Ivan Sopushynskyy, Pavol Otepka, Ljupco Nestorovski, Mário Costa, Abel Rodriguez,
David Rossney, Philippe Ruch, Petros Tsioras, Karl Stampfer, Matevž Mihelič, Nike Krajnc,
Vasillaq Mine, Piotr Mederski and Andrew McEwan

INTRODUCTION

Coppice is a traditional form of forest management that has been widely practiced in Europe since ancient times. Some studies quoted that, in the Mediterranean area, coppiced forests were already established in the Etruscan-Roman period (Matthews 1989, Gabbrielli 2006).

The management system relies on the ability of broadleaved tree species to regenerate quickly from cut stumps and root systems following felling. Both the size of felled area and periods between felling vary depending on the silvicultural needs of different species and local economic factors.

Typical rotation lengths and species in different countries are detailed in the table below.

Coppice management usually provides a regular supply of small dimension material after just a few years of growth. The continued popularity of this type of forest management may be attributed to a relative ease of management and the fact that it is still possible to practice coppicing satisfactorily without large capital investment. Farmers and loggers can cut stools with simple and affordable tools, obtaining products that can serve multiple purposes. The felled stems are often small enough to be easy

Table 1. Most common rotation ages and species in some European Countries (compiled based on the experience of report authors)

Country	Rotation (Years)	Species
Finland	5 - 6	Willows
Slovakia	10 - 30	Birch, Oak spp.
Portugal	12 - 30	Chestnut, Eucalypt, Oak spp.
Italy	12 - 40	Beech, Chestnut, Oak spp., Hornbeam
Spain	15 - 30	Beech, Chestnut, Oak spp.
United Kingdom	10 - 50	Ash, Birch, Chestnut, Hornbeam
Greece	10 - 50	Beech, Chestnut, Oak spp.
Albania	10 - 60	Arbutus, Oak spp.
France	10 - 60	Beech, Chestnut, Hornbeam, Oak spp.
Macedonia	30 - 60	Ash, Beech, Oak spp., Hornbeam
Slovenia	30 - 60	Beech, Chestnut, Robinia
Ukraine	30 - 60	Ash, Alder, Beech, Birch, Oak spp.
Poland	60	Alder

Corresponding author: Natascia Magagnotti, magagnotti@ivalsa.cnr.it

to handle manually, with simple/low specification mechanized forestry systems or with tools already in use on the farm or for other purposes (i.e tractors, trailers, horses, etc.). Furthermore, coppiced forests are usually harvested during winter and this fits well with the work timetable of farmers.

The final harvest of a mature coppice forest commonly yields between 90 and 200 m^3/ha, depending on species, age and site productivity. Stems cut in coppice stands are generally transformed into small-size assortments. Average stem size varies between 0.05 and 0.25 m^3.

Historical and Current Trends

Coppice forest management increased with demographic growth during the 17th-19th centuries and with early industrialization (iron industry, glass factories, tile and lime kilns) which created high demand for firewood and charcoal, especially if coal was not locally available (Parde 1991, Woronoff 1990).

In the past century, with the widespread use of other energy sources such as gas and oil and the use of posts and poles made of concrete or from coniferous species, coppicing entered a period of decline and many coppiced forests became neglected. Furthermore, the migration of people from villages to towns contributed to the abandonment of rural areas and consequently also of the forests.

Now, due to higher fossil fuel prices and efforts to replace fossil fuels by CO_2 neutral renewable energy, there is once again a strong demand for relatively cheap fuel wood. However, this increase is only in part a demand for traditional small-scale firewood; it also includes large commercial operations that supply both domestic and industrial biomass markets.

There is also an increasing demand for ‘environmentally friendly’ materials for use in agriculture, horticulture and in bioengineering, such as soil and bank protection, which means that coppice products have a ‘second chance’ to satisfy these needs.

The general trends of coppice over the past centuries can be summarised as long-term growth, a period of short-term decline and, currently, recent revival.

WOOD PRODUCTS

Firewood

Firewood was the first source of fuel and has always been used for heating, cooking and lighting. Historically, small diameter trees were cut for fuelwood and species more useful for building purposes were conserved. Firewood was never completely surplanted by fossil fuels and it enjoyed a revival in recent years with the increasingly severe oil crisis (Warsco 1994). In fact, Europe still uses more traditional firewood than any other industrial energy wood product (Nybakk et al. 2003). In total, Europe consumes over 100 million solid m^3 of firewood per year, about twice as much as US and Canada put together (FAO 2007).

The production of firewood exceeds 17% of the total wood production in Norway, whereas in Finland and Sweden the level is nearer 10%. In Central Europe, firewood production reaches up to 50% of the total wood production (e.g. Hungary 52%) and in some Southern European countries it reaches more than 70% (e.g. Italy 70%, Greece 72%) (EUROSTAT 2015).

Firewood consumption reached 22 million m^3 solid in France (Elyakime and Cabanettes 2013), about 2.5 million m^3 in Spain, 18 million m^3 in Italy (Caserini et al. 2008) and Slovenian households used about 1.1 million m^3 of firewood every year (Čebul et al. 2011).

Figure 1. Firewood from coppice: piled at the roadside, near the forest and ready for transport (on the left) and split thereafter (right) (Photos: Ivalsa)

Firewood (Figure 1) is extracted from the forest in different lengths, from 2 to 6 m in northern Europe, and from 1 to 2 m in southern Europe, due to the different extraction methods (Magagnotti et al. 2012, Zimbalatti and Proto 2009). It is sold to consumers both as roundwood and as split logs in different lengths (typically 25-30-50 cm or 1-2 m billets).

Most common species used for firewood are beech, oak spp., black locust, hornbeam, ash and alder. Traditionally, chestnut has not been popular as firewood for an open fire because of its tendency to crack and spit during the burning process. Nowadays, with the modern enclosed fireplaces and downdraft boilers, these disadvantages are not as relevant; chestnut has become more widely used, especially since it is more readily available and the price is lower compared to other species.

Firewood has a strong presence in today's markets. In the future a possible slow decline is predicted due to wood stoves and boilers with high energy efficiency and the replacement of solid wood with the new technologically-advanced user-friendly wood-based fuels, namely wood chips and pellets.

Charcoal

Charcoal is produced from hardwoods, such as oak, beech, birch, hornbeam, by pyrolysis and is a porous solid fuel having a high calorific value (31MJ/kg). Therefore, the combustion of charcoal gives off high heat, without flames. The main advantage of the product is that the combustion emits no harmful emissions (tar, tannins, methane, etc.). These qualities have led to the product being widely used for domestic purposes: charcoal is popular choice for outdoor cooking.

In former times, charcoal was produced directly in the forest and you can still find small flat spaces in coppice forests where the simple earth kilns were operated. It is suitable for a large variety of domestic and industrial uses. As "active coal" it is also used as an absorbent material in filters and as a reducing agent in metallurgy. It can easily be transported and stored.

Nowadays charcoal represents a minor market in the EU, although there are exceptions. In the Carpathian mountains of Ukraine, there are notable examples of industrial charcoal-making operations, developed for the export markets over the past 5 years, and currently turning over 0.5 million m^3 of wood into charcoal. Traditional production methods can also be revived to link cultural heritage with tourism; in Slovenia, for example, a private forest owner cooperative successfully markets traditionally produced charcoal as a cultural product, for use in outdoor cooking, while the local municipality offers tourists the opportunity to experience this traditional activity.

Chips

Wood chips are wood particles with a length of 2-5 cm, a width of 2-3 cm and a thickness of few millimetres (Figure 2). Chipping is a common way to process woody biomass from coppice woodland, mainly processing the residues and non-firewood species. The efficiency of the operations is determined by appropriate chipper selection and work techniques (Figure 3). Generally, chips are obtained from forest residues like branches and tops while trunks are used for firewood or poles. This holds true as long as the prices for firewood or poles are higher than the price for chips.

Species such as poplar or willow from short rotation coppice that do not have an alternative market are ideal for chip production.

Figure 2. Example of wood chips

Figure 3. Chipper working at the landing, chipping coppice wood

Figure 4. Chestnut poles that have been debarked and sharpened (Photos: Ivalsa)

Chipping has the potential not only to increase the total harvest through a better utilization of the available above ground biomass, but also gives a solution to the problem of residue management (Pottie and Guimier 1985, Asikainen and Pulkkinen 1998). The demand for chips is linked to the uptake of modern boilers and power stations that are more efficient and have lower emission rates than traditional stoves (Strehler 2000).

Industrial Roundwood

Coppiced beech and chestnut from France and Spain is used in industries producing paper, board and panel materials. In 2014, approximately 4.4 million m^3 of industrial hardwood was used in France (two pulpwood factories in France, as well as one in Belgium, plus about 10 panel and board factories) (Agreste 2014). Eucalypt from Spain, Portugal and South Africa is used in many pulp and paper mills.

Poles, Posts and Other Fencing Assortments

Traditionally, the three coppice species chestnut, oak and black locust have been preferred to produce posts and poles because of their natural resistance to decay, which is particularly important for materials that have contact with the ground. With increasing environmental awareness and concerns regarding the use of chemicals for preserving softwood species, these coppiced alternatives are becoming popular once more (Figure 4).

Larger diameter poles are used in land consolidation works, such as revetments and can be durable for up to 50 years, while small diameter poles are used for gardens and small holdings. Chestnut poles have been used in vineyards since ancient time.

Even today there is an industrial scale production of vineyard poles in Italy, regionally concentrated close to wine-producing areas. It is heavily modernised to remain competitive with alternatives such as concrete, steel and impregnated softwood.

UK and France have extensive experience in splitting bigger coppice boles to produce fencing materials, but many other types of fencing also exist (Figure 5).

Production of oak poles and similar assortments is limited because the price for firewood from oaks is high compared to other species.

Construction, Furniture and Flooring

Boles of larger dimension from oak and black locust are used as sawnwood for the production of outdoor furniture and solid wood for indoor furniture. A new development is the production of parquet flooring (Fonti and Giudici, 2002) with high resistance and beautiful colour in two main products: the so-called “mosaic” and “laminated, ready to lay”. Chestnut wood is also used for outside decking thanks to its resistance to weather conditions.

In Austria, cherry from 40 year old coppice forests is used to make high value furniture. In Poland, long rotation coppice alder is used to produce high quality plywood.

Craft Products

A number of other wooden objects can be obtained by material from coppice forests. In most cases they are made by artisans as locally produced handicraft souvenirs and include items such as baskets, walking sticks, carvings, sculptures, toys and eating utensils (plates, spoons, etc).

Figure 5. Example of fencing in the field (Photo: Ivalsa)

NON WOOD PRODUCTS

Coppice forests can provide many non wood forest products with great potential and market. For extensive research on non wood forest products in general, see COST Action FP1203 “European non-wood forest products” (www.nwfps.eu).

Some examples of non wood products from coppice forests are:

Honey and Beeswax

Honey (Figure 6) is used as sweetener in many recipes and as a spread, but also in medical traditions to treat wounds and coughs. Honey is also the main ingredient in an alcoholic beverage called mead. Honey is mainly from chestnut, black locust, eucalypt and linden. Honey and beeswax are used in the cosmetic and pharmaceutical industries as well.

Mushrooms and Truffles

Many edible mushrooms grow in association with chestnut or oaks – including truffles (*Tuber* spp.) and porcinis (*Boletus edulis*), both highly prized in many countries as side dish, or with rice, pasta and meat. Truffle oil is a delicacy made from high quality olive oil infused with concentrated truffles (mainly black winter truffles).

Figure 6. Honey produced in *Salix* coppice stands; prepared as a taste-testing to compare different honey types (Photo: D. Lazdina)

Fruit

Local fruits and nuts are harvested from coppice woodland on a small local scale and can be important to some communities.

Traditional Medical Herbs

Some non wood products are used as medicinal herbs in the Ukraine and the Republic of Macedonia.

Game

The habitats provided by managed coppice forests are ideal for many animal and plant species that are adapted to particular levels of open space and shade. Some game species also find the habitats suitable, so coppice is often exploited for rearing and hunting.

Biochemicals

Tannin is utilized mainly from chestnut and oaks. It is prepared by hot water extraction of the bark and timber, followed by spray-drying of the solution. Vegetable tannin was used for leather production, but its use has decreased since the 1950s because of synthetic tannins. Nowadays its characteristics are appreciated for premium quality leather.

NEW PRODUCTS AND THEIR PROMOTION IN THE FRAMEWORK OF A GREEN ECONOMY

The demand for coppice products has recently been increasing, mainly for energy purposes. This trend is in part influenced by the recent developments of management techniques, both in harvesting and processing technology. For example, it is quite common to have integrated recovery of logs for firewood and poles, and branches and tops for chips. It is likely that in many countries the use of wood chips will increase.

The trend of the increasing demand is not homogenous in all regions due to different forest, economic, cultural and social aspects. For example, chestnut demand for furniture production is higher in central Italy, while the production of chestnut laminated beams and panels is increasing in north-eastern Italy (Pettenella 2001).

The development of new markets and green economies can be supported by new management and marketing instruments, such as new approaches in the selling system, efficient promotion and certification.

It is not easy to find the right “recipe” for promoting the use of coppiced products in the framework of a possible green economy. These trends and markets are at different levels in different countries, according to economic, environmental and social conditions and to species composition.

There are some instruments that can promote and boost the market chances:

- **Networking, association and promotion:** reinforcement of the producers’ market power.
- **New selling system:** small local markets, which permit the local producers to sell directly to consumers; E-business; Business to business with the sales of semi-finished products and DIY (do it yourself) products.
- **Promotion of legal labour:** because of less taxes and minor costs, companies with illegal workers can sell products – especially firewood – at lower price, causing a distorted market.
- **New developments in harvesting and processing technologies:** in recent years, new technologies that require different levels

of power and investment have arrived on the market. There is a wide choice of tractors, trailers, winches, cable-yarders, fire-wood processors, chippers and many more. Public administration should control and promote training courses in safety and technical matters. Short and practical training courses could help logging companies in increasing their competitiveness and productivity.

- **Promotion by public authorities:** the use of coppiced products could be encouraged through regulations, public investments and promoting programs. For example, a municipality could use benches made from chestnut wood in public parks, or stimulate the use of chestnut poles in vineyards and when installing wooden highway barriers. Cooperation between public authorities and producers could be one success factor in promoting and developing coppiced products. Another is increasing the coordination between local producers.
- **Diversification of products:** to enter and/or develop profitable markets and empower forest owners and operators. In many situations, high firewood prices discourage the production of other assortments, such as poles. However, the economic benefit of good firewood prices can be uncertain since it can change under many circumstances, such as new products, warm winters or regulations on the air quality allowed in old stoves. A possible addition could be, for example, pellets and microchips; the market is currently booming and the products are easier to manage and more suitable to modern life style. Operators should try to diversify their production with a wide range of valuable assortments.

CONCLUSIONS

In the past, vast areas of coppice forest in Europe supplied the local population with products such as firewood, charcoal, tannin, and fodder, as well as shelter for animals and a large variety of poles used in agriculture and construction.

Despite some decades of decline, the current economic trends point to a good future for coppice management. It has the potential to gain importance again locally, strengthen rural communities and help avoid the depopulation of mountainous regions and other rural areas.

The current danger is that neglective or disruptive management activities can have more serious silvicultural and ecological consequences than in more ‘natural’ forest systems. Thus, abandoning coppice forests may not only lead to to an impoverishment of rural communities, but also to environmental degradation and ecological catastrophes.

Without active management there will be no coppice and without income from coppice, there will be no management. Therefore, rural development policies should encourage and promote the diversification of rural activities and multi-functional models that are suitable for coppice forests.

In addition to the traditional products already mentioned, there are new products that are valuable in the context of the green economy, particularly in the area of energy. One priority should be to promote the efficiency of coppiced forests and to pursue this management as a system. It is not seen to be viable to create more coppice from high forest, but to try to dissuade foresters from trying to convert more coppice to high forest. Coppice forest will only be able enjoy the benefits of the modern green economy if coppice management is modernized.

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Guidelines for Coppice Forest Utilization

Natascia Magagnotti, Janine Schweier, Raffaele Spinelli, Petros Tsioras, David Rossney,
Eduardo Tolosana, Abel Rodrigues and Stefan P. P. Vanbeveren

1 INTRODUCTION

Coppice management is extremely efficient; it offers the benefits of easy management, prompt regeneration and a short waiting time. Efficiency is also achieved during harvesting, because coppice is often clearcut, which allows concentrated harvest and simple felling arrangements. On the other hand, coppice management has some important limitations, especially the relatively small tree size and the exclusive reliance on hardwoods, which tend to limit future product outputs and productivity.

In recent years, new applications of the coppice concept have been developed for industrial use and/or for a changing agriculture. Today, we may identify three broad types of coppice stands, as follows (Table 1):

Table 1. Three types of coppice stands that have implications for utilization practices

		Conventional Coppice	Short rotation forestry (SRF)	Short rotation coppice (SRC)
Species	(type)	*Quercus* sp. *Fagus sylvatica* L. *Ostrya carpinifolia* L. *Castanea sativa* Mill. etc.	*Populus* spp. *Eucalyptus* spp. *Acacia* spp.	*Salix* sp. *Populus* sp. *Eucalyptus* sp.
Rotation	(years)	15 - 30 / 40	5 - 15	1 - 5
Product	(type)	Firewood	Pulpwood	Chips
Economy	(domain)	Industrial and small-scale forestry	Industrial forestry	Industrial agriculture
Harvest	(technology)	Forest	Forest	Agriculture

Corresponding Author: Natascia Magagnotti, magagnotti@ivalsa.cnr.it

Conventional coppice (Figure 1)
Established with indigenous hardwood species (oaks, chestnut, beech, hornbeam etc.) and occasionally exotic ones (*Robinia*). It is usually harvested on 15-30/40 year rotations for a large variety of products and is managed within the framework of a rural economy, according to local traditional practice. It is harvested using a wide range of techniques and usually uses equipment from small scale agriculture, although the use of specialized forestry machinery is increasing.

Figure 1. Motor-manual felling in a conventional chestnut coppice

Short rotation forestry (SRF) (Figure 2)
Stands are established with exotic fast-growing species (*Eucalyptus, Acacia*) and harvested on 5-15 year rotations to produce industrial feedstock (generally pulpwood). SRF is often developed within the framework of a large-scale industrial economy to supply industrial plants. SRF stands are often (but not exclusively) managed as coppice and they occasionally undergo shoot reduction treatments (thinning). Stands are generally harvested with industrial forestry equipment, but also occasionally with small-scale forestry equipment.

Figure 2. Mechanized industrial felling in a eucalypt SRF plantations managed as coppice (Photo 1 & 2: R. Spinelli)

Short rotation coppice (SRC) (Figure 3)
Stands are established on ex-arable land with fast-growing species, indigenous (willow, poplar) or exotic (*Eucalyptus, Robinia*). They are harvested on 1-5 year rotations to produce industrial feedstock (generally energy biomass) and managed within the framework of small-scale or industrial agriculture. So far, SRC represents a niche sector and it is generally harvested with modified agricultural equipment.

Figure 3. Single-pass harvesting in SRC established with willow (Photo: J. Schweier)

2 CONVENTIONAL COPPICE

The traditional management of conventional coppice forests is quite simple and is based on clear cutting at the end of rotation. Standards may be released in conventional coppice, with a density ranging from 50 to 100 trees per hectare (ha), depending on the species. No standards are released in SRF and SRC plantations. The final harvest of a mature coppice stand commonly yields between 90 and 200 m^3 ha^{-1}, or more, depending on species, age and site productivity. The harvest obtained from thinning (conversion) over-mature coppice generally varies from 40 to over 200 m^3 ha^{-1}. Generally, clear-cutting accrues profits, whereas thinning (conversion) generates losses.

Management has a strong effect on product type and harvesting productivity. Stems are cut before they can become very large and are best suited for conversion into small-size assortments. Mean stem volume typically varies between 0.05 and 0.25 m^3.

High production capacity is only achieved through the increased mechanization of harvest operations, which also helps to compensate for the effects of high labour costs and increasing labour shortages experienced in most industrialized countries (Spinelli and Magagnotti 2011). Technological progress has made the effective introduction of mechanized felling to coppice operations possible, significantly increasing worker safety and productivity. Professional management of mechanized harvesting can prevent or minimize undesired effects, such as soil, stump and stand damage (Cacot et al. 2015). When mechanized harvesting is applied, the scale of the operation and the wood removal must be large enough to offset the high fixed cost of moving machines to the worksite (Väätäinen et al. 2006).

Work safety has become a priority across Europe and the rate and severity of accidents in mechanized felling is much lower compared with the motor-manual option (Albizu et al. 2013).

2.1 Products

Europeans have exploited a wide range of broadleaved tree species in woodlands since the Stone Age. In fact, this prehistoric period of human evolution might more accurately be called the 'Wood Age', reflecting the over-riding importance of wood-based technology at this historic period.

Our ancestors learned to harness the ability of broadleaved tree species to sprout and re-grow when cut. This typically yielded multiple stems, the size of which simply depended on the time they were left to grow. The multiple shoots tended to yield sticks and poles that were straight-grained and relatively branch free; properties that still prove useful to us today.

The lightweight and straight material made good weapons (spears, bows and arrows), tool handles for axes, blades, adzes and ploughs, fencing and building materials (Figure 4). The straight grained wood split easily, yielded

Figure 4. Split chestnut gate hurdles by G and N Marshman Ltd. West Sussex, UK (Photo: D. Rossney)

almost limitless possibilities for strong but lightweight product designs and dried quickly and thoroughly, as is important for firewood.

Traditional products may be categorized as follows:

Building Materials

Includes whole stems (ca. 20 cm +) used in the round, hewn by axes into square sections, riven (split by hammer and wedge) and latterly sawn and jointed into the variety of dimensions required for timber framing.

Dwellings, fencing and weaving

Younger coppice poles have been used from earliest times to construct dwellings and fences, typically with durable species such as sweet chestnut and oak, if these were available. Hazel is less durable, but widespread and capable of producing large quantities of long clean rods. Such characteristics are ideal for a variety of products, such as woven panels used as 'hurdles' for fencing animals; 'wattle and daub', which is an in-filled stick and mud wall in timber framed buildings; and even small, round, skin covered boats called 'coracles', which were used in England during the Iron Age (Figure 5).

Figure 5. Examples of coracles by Guy Mallinson Woodland Workshop, Hereford, UK (Photo: D. Rossney)

Fuel

Firewood for heating or cooking has always been a large consumer of coppice wood, including the use of 'faggots' (or 'slash bundles'; bundled sticks), which give quick heat for bread ovens. Coppice was also turned into charcoal wherever fuel was required for smelting metal, until this practice was superseded by coking coal. In areas with iron ore, where no coal existed, industrial-scale coppicing and charcoal production continued into the 20th century.

Other products

These included bark for leather tanning and weaving, fruits and nuts, such as chestnuts (Figure 6) and hazels, foliage as fodder for animals, pannage (seasonal practice of feeding pigs in woodland on fallen acorns and other nuts) and collected herbs, fungi and medicinal plants growing in coppice woodland ecosystems.

In addition, there are household products that make use of small-dimensioned material, which is 'woven' into small (decorative) creations/ objects, for example, small baskets and brooms. These products have been used through the ages, and still are today. An important market now is for tourists or city dwellers purchasing them (mostly) out of nostalgia, which affords an opportunity for some rural communities to earn part of their living from this activity.

Figure 6. Chestnuts, one of many coppice products (Photo: R. Spinelli)

Figure 7. Extraction of firewood with pack mules (Photo: R. Spinelli)

2.2 Harvesting

Traditional harvesting systems

In ancient times, manual work was dominant and it made sense to reduce cut stems to such a size that could be easily handled manually. Firewood was typically cut into one-meter lengths at the stump site, before loading it on pack animals for extraction and transportation (Carette 2003) (Figure 7). With minimal adjustments, animal extraction remained in use until a few years ago in industrial countries such as Italy and France (Baldini and Spinelli 1989) and it is still widespread in the Balkans. Modern adaptations to this ancestral system have been the introduction of chainsaws for felling and processing and of trucks for transportation, so that animal work is limited to extraction. Small stem size, an uncomfortable working position and the need to cut stems into manageable lengths result in a very low productivity of motor-manual felling and processing, which is reported in a range between 0.3 and 1.4 m^3 per scheduled machine hour (SMH) per operator (Spinelli et al. 2016a).

Modified traditional harvesting systems

The search for a mechanical substitute for the traditional mule started in the late 1980s. Over time, various micro-tractors have been designed and tested (Magagnotti et al. 2012), but none have ever obtained commercial success. Eventually, pack-mules have been replaced by the so-called pack-tractor, i.e. a farm tractor equipped with front and rear bins capable of containing ca. 3 tonnes (t) of one-meter logs (Piegai and Quilghini 1993). Small payload size prevents efficient use of these vehicles on distances further than a few hundred meters, while the limited mobility of an encumbered farm tractor limits its use to relatively easy terrain, or areas with a good network of skid trails. On suitable terrain, productivity is higher than reported for mule teams, varying from 2 to 4 m^3 SMH^{-1} with a crew of two (Spinelli et al. 2016a).

Mechanized cut-to-length harvesting

Mechanized cut-to-length (CTL) harvesting (Figure 8) is based on the introduction of the classic harvester-forwarder combination. While representing a radical technological innovation, CTL harvesting is not a revolutionary system change because it includes the same task sequence followed in the traditional system. The system is adapted to mechanization by increasing log length to 2 or 3 m, since one-meter long logs are too short for efficient mechanical handling. Appropriate machine choice and operator skill are necessary when applying CTL harvesting to coppice stands. The

Figure 8. Mechanized cut-to-length harvesting (Photo: R. Spinelli)

productivity of a modern harvester deployed in conventional coppice operations may vary from 2 to almost 10 m^3 SMH^{-1}, depending on stem size and operator proficiency. The productivity of the forwarder commonly ranges between 5 and 10 m^3 SMH^{-1}, depending on machine model and extraction distance (Spinelli et al. 2016a).

Whole-tree harvesting

Whole-tree harvesting (WTH) consists of felling trees and extracting them whole to the landing, where they are processed into commercial assortments. The main advantages of WTH are the simple in-forest handling, as well as postponement of processing to the landing, where it can be mechanized if terrain constraints make the stand inaccessible to harvesters. Motor-manual directional felling may proceed at a pace between 1 and 4 m^3 SMH^{-1} $operator^{-1}$. If terrain is accessible to mechanical equipment, then feller-bunchers can be introduced and productivity will increase dramatically, reaching values between 4 and over 8 m^3 SMH^{-1} (Schweier et al. 2015). The main operational benefit of mechanized felling is that the better presentation of felled trees boosts extraction productivity. This may range from less than 3 m^3 SMH^{-1} for skidding with a forestry-fitted farm tractor to 5 or even 8 m^3 SMH^{-1} when a dedicated skidder is used. On steep terrain, cable yarding (Figure 9) is the cost-effective alternative to building an extensive network of skidding trails and results in a much lighter site impact compared with ground-based logging (Spinelli et al. 2010). Productivity is somewhat lower than in ground-based operations, varying from 3 to 7 m^3 SMH^{-1} (Spinelli et al. 2014). The main difference with ground-based extraction is crew size, which increases to 3 or occasionally 4 workers, whereas only 1 or 2 workers are required for a skidder.

Figure 9. Cable yarding on steep terrain (Photo: R. Spinelli)

Once at the landing, whole trees are converted into conventional assorted products (i.e. firewood, pulpwood etc.) or thrown straight into a chipper. Whole-tree chipping was tested relatively early on in the Italian coppice stands (Baldini 1973) and has become a widespread commercial activity over the last decade due to a booming demand for biomass chips.

Despite all its many advantages, WTH must be considered with some caution because of the risk of soil nutrient depletion (Helmisaari et al. 2011).

Tree-length harvesting

In tree-length harvesting (TLH), trees are delimbed and topped before extraction, but not cut to length. It reduces inefficient stump-site work compared with traditional short wood harvesting, but increases the retention of biomass on-site, helping to mitigate possible adverse effects and making it suitable for site of low fertility (Mika and Keeton 2013). TLH operation determines a large (>50%) increase of stump-site work compared with WTH, whereas landing work is reduced only slightly. Decreased work efficiency leads to a general increase of logging cost, which has been estimated at 10-15% over WTH (Spinelli et al. 2016b).

3 SHORT ROTATION FORESTRY

In Europe, short rotation forestry (SRF) stands, planted with exotic, fast-growing species and managed as coppice, are mainly located in the Iberian Peninsula. Among these fast-growing species, *Eucalyptus* is the most prominent and is cultivated for pulp and paper industry; it will be the focus of this chapter.

Eucalyptus was first planted in the Iberian Peninsula in Vila Nova da Gaia (Portugal) in 1829, while the first eucalypts planted in Galicia (Spain), around 1850, were likely *E. globulus*. Nowadays, the estimated surface of eucalypt plantations is approximately 0,8 Mha in Portugal and 0,6 Mha in Spain. The Iberian eucalypt industrial wood production was estimated at 10,9 Mm^3 in 2009, which represented 47% of the industrial wood fellings, but only 6% of Iberian forest surface.

3.1. Products

The main planted *Eucalyptus* species is *E. globulus*. It is very efficient in cellulose fiber production, so the main destination of its wood is the pulp industry. There are several pulp mills of different companies operating in Spain and Portugal and in 2009 they had a demand of nearly 12 Mm^3. Nowadays, *E. globulus* occupies the largest forest area in Portugal with 812.000 ha, mainly allocated for pulp production under an intensive coppice system, with a full year growing cycle. *E. globulus* is the only significant eucalypt species in Portugal.

Other uses of eucalypt forests are less frequent, but there are some smaller mills producing veneer, laminated panels and beams used for farming mussels beneath sea water. In addition, essences and honey are widely obtained from these cultivated forests.

3.2. Harvesting

E. globulus is a sprouting species and is thus traditionally coppiced. In the past, the more drought-resistant *E. camaldulensis* was widely planted in the southwest of Spain, but in the past decades most of its plantations have been removed or substituted by more productive *E. globulus* clones. Lastly, from the beginning of 21st century, the more freeze, pest and diseases resistant species *E. nitens* has become more frequent in the northwest of Spain, especially in Galicia.

The most productive Spanish eucalypt plantation area is located within Galicia and the Cantabrian region. A constraint on these plantations is the very fragmented forest ownership (average ownership size of less than 2 ha, divided into several plots), which limits the harvesting systems and the plantation profitability. Accordingly, most of the Spanish harvesting contractors are small-sized enterprises that have had trouble to adapt to a proper mechanization due to lack of investment capability and, in many cases, lack of adequate training and entrepreneurial culture.

In Spain, the usual plantation frame ranges from 2x3 m to 3x3 m (final density; there are no thinnings) and the rotation age varies from 12 to 15 years, although it could eventually be longer. Fertilizing and cleaning of competing vegetation are usual practices. Treatments against pest and diseases are quite common. Fire risk and fire protection are of high importance for eucalypt management.

When a *E. globulus* plantation is coppiced, felling and sprouting are followed by the selection of the best sprouts: 1 to 3 per stump, after 1 or 2 years. The second rotation is thought to produce some 10-15% more volume

Figure 10. Felling by chainsaw
(Photo: E. Tolosana)

compared to the original plantation, while the next rotations continue to decrease in yield to the point at which it is more productive to plant again. During the past decade, many coppices have been uprooted and re-planted again using genetically improved material.

Eucalypt coppices in Portugal are characterized by a 12 year rotation cycle and that growth continues throughout the year. The average biomass productivity ranges from about 14 to 16 t ha^{-1} year^{-1}, which is equal to about 14 to 15 m^3 year^{-1}. Recent data shows a high dependence between biomass productivity and rainfall, reflected by a sharp decrease in the second year of a two year draught period (2004 - 2005), characterized by half yearly precipitation values. The decrease of above ground biomass productivity in the second year was half the order of magnitude compared to usual values.

The traditional logging systems are based on:

Motor-manual felling and processing

With chainsaw; where forest harvesters are not available and/or the terrain conditions are unfavorable for mechanization (Figure 10).

Semi-mechanized felling and processing

Felling by chainsaw and processing using forest CTL-harvesters, frequently based on tracked excavators but also specialized Nordic machines. One of the reasons felling often has remained to be motor-manual is the interest of the forest owners in keeping the stump height as low as possible and getting a good cut quality. In steep terrains, felling is always performed by chainsaw. Whole trees are then slipped or winched to temporary forest roads where they are processed by machines.

The most common equipment for extraction is an adapted farm tractor or local small to medium-sized forwarder, using the CTL harvesting system.

The use of residual biomass in Spain has changed over the years. In the past, the logs were debarked at the harvesting site and branches, tops and bark left on the terrain. From the 1990s onwards, the trend has been to transport the wood with bark to the mill (Figures 11) and use stationary drum debarking machines to separate the bark, which is burnt for combined heat and power (CHP) generation at the mills.

Felling mechanization in eucalypt plantations has been encouraged in the past years.

Figure 11. Transportation of wood with bark to the mill (Photos: E. Tolosana)

Figure 12. Mechanized felling and processing

Figure 13. Mechanized felling (Photos: E. Tolosana)

Besides the traditional systems mentioned above, companies are trying to implement two new harvesting systems:

- Fully mechanized felling and processing with specialized forest harvesters (Figures 12 and 13)
- Fully mechanized felling with disc saw or knife feller-buncher, followed by processing with forest processors

To haul the logs off, the trend is to use larger, increasingly Nordic, forest forwarders.

Regarding eucalypt residual biomass harvesting in Spain, the prevalent system is based on bundlers (Figure 14); Portuguese or Nordic machines equipped with knives - instead of chainsaws - to cut the biomass bales. This allows the use of the same machinery to handle the logs and the bundles and avoids the preparation of landings to organize chipping operations, which is often difficult in the typically small plantations.

Besides this, one of Spain's leading forest management companies, ENCE, is trying to improve forest harvesting operations by providing their logging contractors with Total Quality Management (TQM) instructions, in order to increase the utilization rate and productivity. To this end, ENCE has developed apps that communicate daily reports by the contractors through mobile phones and they are providing their contractors with technical and managerial support to optimize their operational efficiency. Despite the inclusion of a GPS tracking system, the road transport optimization still has much room for development.

There is a recent strong trend to substitute *E. globulus* with *E. nitens* in some Galician forest areas despite the fact that the latter is less efficient in producing cellulose fiber and does not resprout well, which limits coppicing. The main drivers are the threats by pest and diseases, towards which *E. globulus* is more sensitive, and the much higher growth potential of the *E. nitens* in many climate and terrain conditions.

Besides this species change, in Spain there is a trend to abandon coppicing in some areas; mainly where *E. nitens* is planted, but also other areas. Some reasons are: coppicing requires a more intense management than first plantation at final density; pulpwood quality is worse in coppice; coppice harvesting presents some mechanization difficulties; there is a decrease in yield after multiple coppicing; and new technologies allow the production of pulp from removed stumps.

In Portugal, the main trends of pulp production follow a consequent forest biotechnological breeding program of *E. globulus*, which aim at improving the biomass productivity and resistance to biotic and abiotic agents, such as drought.

Figure 14. Bundler, often used for eucalypt in Spain (Photo: E. Tolosana)

4 SHORT ROTATION COPPICE

Short rotation coppice (SRC) is a dedicated crop, mainly planted on agricultural land and designed to produce large quantities of raw materials at regular intervals.

Fast-growing tree species considered for SRC can be indigenous (willow, poplar) or exotic (eucalypt, black locust).

The planting density ranges from about 6,000 to 15,000 plants (usually unrooted cuttings) per ha, planted in single or twin rows, according to the species and the rotation lengths. The tree growth is influenced by site characteristics (such as soil and climate) and genotype selection should be made accordingly. SRCs are harvested in rotations of 1-5 years for the production of industrial feedstock (generally energy biomass).

The plantations are generally harvested with modified agricultural equipment that can harvest small stems. Forest equipment is only used if stems are too large and too close to one another. Planting is done with vegetative material (uprooted cuttings), whereas resprouting after harvest happens naturally from the existing root systems.

4.1 Products

The main purpose is to grow wood for energy (Figure 15), but it also can be used for other products, such as industrial feedstock or in the bio-refinery industry. In most cases, stems are chipped immediately after the cutting and blown into a tractor-trailer unit that accompanies the forage harvester. These chips have a moisture content of 50-60% (Spinelli et al. 2008, Vanbeveren et al. 2015) and a low heating value. Chips can be dried (naturally or

Figure 15. Short rotation coppice crops are mainly chipped and used for energy (Photo: J. Schweier)

Advantages of SRC

- High biomass yields
- Regular incomes in short intervals
- Groundwater protection
- Ecological planning
- Phyto-remediation
- Increase of value added in rural areas
- Diversification of landscape
- Higher biodiversity compared to agricultural fields

Disadvantages of SRC

- High moisture content of freshly cut chips (poplar 50-60% wet weight basis)
- Difficult storage of wet chips
- Technical limitations on difficult terrain (slope)
- High costs on small sites
- Dependence on harvester availability
- Lower biodiversity compared to forests and uncultivated grass/shrublands

Figure 16. Unloading of chips; the chips should be used immediately if possible (Photo: J. Schweier)

artificially) to reach a desired moisture content. However, during the storage there is a dry matter loss of 10 - 20% (Schweier et al. 2017) due to microbiological activities, which reduce the chip quality and can create self-ignition and health problems. The latter are caused mainly by fungi, especially when their spores become airborne during fuel handling. Therefore, chips should be used immediately (Figure 16). If this is not possible, chips should be stored at a proper distance from residential areas and should be handled with appropriate precautions.

If the market recognizes the added value, the use of surplus heat, when available, could be a good and efficient option for drying chips (Schweier and Becker 2013).

Chips from SRC have a relatively high bark content, which is important because bark has higher elemental concentrations and a lower density compared to wood (Tharakan et al. 2003). During the combustion of material with a high bark percentage, problems arise from damage to the boilers (Guidi et al. 2008) and fouling can occur. Bark ratio is reduced in biannual systems, where harvesting is done at minimum 2 - 3 year intervals, which produces more favorable chip quality than annual harvesting. Therefore, clones with a lower bark percentage should be selected and trees should not be cut before an acceptable fibre-to-bark ratio is obtained (Spinelli et al. 2009).

4.2 Harvesting

There are two dominant harvesting systems used for SRC: the single pass cut-and-chip and the double pass cut-and-store technique.

Single pass cut-and-chip technique

Stems are cut, chipped and discharged into accompanying tractor-trailer units in one single pass, using only one harvesting machine (Figure 17). Generally, the system is based on a prime mover equipped with a header and 2 - 4 tractor-trailer units to move the chips to a collection point. There, the wood chips can be reloaded onto road transportation vehicles, or used directly as feedstock if an energy plant is close-by.

The coppice header can be placed on the front of the mover or on the side. Headers for SRC can be modified maize choppers (e.g. the Claas HS-1) or purpose-built (e.g. Claas HS-2 or the Italian GBE). According to site characteristics, these machines can reach very high productivities with peak values up to 80 green tonnes per hour (Spinelli et al. 2008) and guarantee consistent chip sizes. An additional advantage of modified forage harvesters is that they allow the farmer to run their machines in winter as well, when agricultural field work is not possible. The main disadvantage is the machines' weight, as this limits their use to flat and solid terrain. Modified forage harvesters require stems of a particular size and row spacing. Cut stems usually enter the chopper horizontally, but if stems are too close to each other, or too long, the cut stems can become entangled with standing stems and jam the header (Spinelli et al. 2009).

Figure 17. Examples of single pass cut-and-chip system: the harvesting machine cuts and chips the stems and the chips are discharged directly into a tractor-trailer units. (Photos: J. Schweier)

Mower-chippers can be a good alternative for dense plantations and larger diameters due to their capability to chip the stem in an upright position (Pecenka and Hoffmann 2015).

Double pass cut-and-store technique

With the double pass cut-and-store technique, the processes of cutting and chipping are split into two steps: one machine first cuts and windrows the stems (Figure 18) and a second picks them up and chips them (usually some weeks to months later), blowing the chip into conventional silage trailers. The main benefits are the capacity to concentrate the cutting within a short period of time (thus exploiting good weather windows) and the possibility to chip the material according to market demand or required moisture content.

Until now, single pass cut-and-chip harvesting is the most common technique used in SRC, due to the technological progress and research that it underwent. Other techniques do exist, such as the singe pass cut-and-bale and the single pass cut-and-billet technique, which produce wood bales in the first case and billets in the latter (Vanbeveren et al. 2017), but they do not yet reach market value. Thanks to their more powerful engine, cut-and-chip harvesters have a higher average productivity (30 green tonnes per hour) than whip harvesters (19 green tonnes per hour) (ibid.).

Conclusions

Among possible sources of energy biomass, SRC has a high potential to contribute to the renewable energy mix.

Since harvesting costs are estimated to be above 50% of the total cost of the biomass produced from SRC, the optimization of these operations is required.

Good performance can be obtained when several factors concur, such as: good terrain and weather conditions, adequate machine selection, appropriate crop density and exact row spacing.

Figure 18. Example of the cutting in the double pass cut and store techniques. The stems will be chipped later (Photo: J. Schweier)

5 CONCLUSION

Despite some decades of decline, the current economic trends point to a good future for coppice forests (Figure 19).

Coppice management can be applied in many ways, according to different species, level of mechanization and specific local condition; it can also be aimed at different products.

Active coppice management already plays a vital part in rural economies, but can increase its potential when a certain level of modernization is acquired.

Mechanization is a possible solution to make coppice management a modern industrial business instead of a part-time activity. Modern harvesting systems, of different scales, can compensate for the difficulty in acquiring sufficient rural labor and maintaining young workers in the forestry sector.

It is important to select or, in some cases, further develop the right felling technology to guarantee the rejuvenation of the coppiced stands. Stump crowding and small stem size can be considered common elements that have an impact on operational choices in many coppiced stands. The presence of multiple stems on the same stump offers a serious challenge to mechanized felling in coppice harvesting operations, because stem crowding hinders felling head movements. Small stem size affects the type of products one can obtain from coppice stands, while limiting work productivity.

An effective introduction of mechanized felling requires the selection of a suitable machine but also a skilled and professional operator who can prevent or minimize undesired effects, such as soil, stump and stand damage.

Figure 19. Coppice provides a wide range of products and is important for rural economies (Photos: upper left C. Suchomel, lower middle R. Spinelli, lower right J. Schweier, rest A. Unrau)

It is also necessary to promote a certain level of mechanization to improve safety. Manual work is associated with the highest accident risk and severity, and it accounts for most of the fatal accidents recorded in forest operations.

Silvicultural practices may need to be adapted to new harvesting technology and to favor, whenever possible, proper removals and the use of machines. In many cases coppice forests are situated in difficult terrain with poor access. The improvement and adaptation of the existing infrastructure (road density and quality) to the requirements of mechanized operations is one important prerequisite for successful mechanization.

Although much progress has already been made, the introduction of mechanized operations still encounters resistance.

Better knowledge concerning the techniques of mechanized harvesting in coppice forests is required. International initiatives such as the COST Action FP1301 EuroCoppice may help to bridge gaps in such areas.

Rural development policies should encourage coppice management in order to promote the diversification of rural activities.

It is important to continue the regular utilization of coppice in order to preserve it as a system of forestry. This utilization will promote ecological, protection and aesthetic functions of coppice forests and can guarantee income to owners, loggers and rural communities.

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Impacts of Coppice Harvesting Operations on Soil

Rodolfo Picchio, Marco Senfett, Irene Luchenti and Rachele Venanzi

INTRODUCTION

Coppice is a traditional method of stand regeneration to produce woody biomass, a management system that is still widespread in many regions worldwide. Until the middle of the 20th century, coppice forests were common in most parts of Europe; although this has since changed, several issues relating to coppicing are still relevant. In Italy, coppice has much economic and social relevance for hilly and mountainous areas. Coppice produces timber for firewood and charcoal production (Picchio et al. 2011b) and has been an important source for litter collection and pasture (Gimmi et al. 2008; Glatzel 1999). At the same time, coppice harvesting could have a significant degrading influence on woody regeneration, fauna and the soil, causing compaction, horizon mixing and topsoil removal (Korb et al. 2007). In particular, compaction reduces both soil porosity and pore connectivity, thus increasing soil density and shear strength (Klvac et al. 2010; Picchio et al. 2012b; Williamson and Neilsen 2000). Such soil degradation can decrease tree growth (Grigal 2000), while carbon dioxide efflux from the soil may change significantly (Olajuyigbe et al. 2012). In this paper, two different coppices were analyzed, characterized by different stand types of Turkey oak (*Quercus cerris* L.) and chestnut (*Castanea sativa* Mill.).

In Italy, the traditional management of Turkey oak is coppice with standards, which involves felling about 80–85% of the total woody biomass and releasing about 70–120 standards/ha. For chestnut, the forests are mainly managed as coppices with standards, for productive and phytosanitary purposes (to cater for bleeding canker or chestnut blight), felling about 85-90% of the total woody biomass and releasing about 30–100 standards/ha. Logging systems may differ, depending on silvicultural management and the final product. The technical and economic utilization of coppice forests depends on various factors, including the type of terrain, transportation networks and harvesting technologies, as well as the silvicultural treatment and logging system (Cavalli and Grigolato 2010; Vusic et al. 2013). Although in recent years significant innovations in the technology and methodology of forest operations have occurred (Picchio et al. 2012a, 2011b), the majority of private and public coppice forests are still harvested using traditional methods, i.e. motor manual felling with chainsaws or using mules and/or agricultural tractors for extraction (Picchio et al. 2011a, 2011b; Laschi et al. 2016). The effects of harvesting can affect changes to the vegetation, nutrient availability, soil microclimate, soil structure and litter quantity and quality (Borchert et al. 2015; Edlund et al. 2013). In particular, operations such as forwarding and skidding have a high potential for causing soil compaction (Jamshidi et al. 2008; Cambi et al. 2015, 2016). However, properly managed forest ecosystems are claimed to be highly resilient in the long term (Sánchez-Moreno et al. 2006). Some studies also suggest that compaction can be avoided by minimizing areas of soil disturbance and soil compaction by designing thinner networks of strip roads (Mederski 2006).

Corresponding Author: Rodolfo Picchio, r.picchio@unitus.it

In coppice management, the time between harvests is called “rotation”, or sometimes also “cutting cycle” (Espelta et al. 1995; Retana et al. 1992). During this time the stands are mostly restocked by natural regeneration through seedlings (gamic) and sprouts (agamic), a process that is strictly dependent on physico-chemical soil quality. This aspect of soil quality should also include some assessment of different biodiversity patterns. Biodiversity conservation has long been a goal of European conservation policy (CBD 2010; CEC 1998) and the monitoring of this aspect is essential to support management decisions that maintain multiple forest ecosystem functions (CBD 2001). A better understanding of the importance of biological diversity is needed to support the provision of multiple forest ecosystem services (Corona et al. 2011; Mattioli et al. 2015).

Within the COST Action FP1301 EuroCoppice, studies specifically designed to analyze the impact of the silvicultural treatment and logging operations on forest soils in coppices were performed using both standard and “innovative” wood extraction systems. In addition to the usual physical and chemical analyses (pH, organic matter, bulk density, penetrometric and shear resistance) (Cambi et al. 2015), an innovative methodology using an arthropod-based Biological Soil Quality index “QBS-ar” was applied (Parisi et al. 2005; Venanzi et al. 2016). The use of this index has valuable potential as a tool in ecosystem restoration programs in monitoring soil function and biodiversity, and in preventing the negative effect of soil compaction due to logging activities (Blasi et al. 2013).

METHODOLOGIES

Similar study methods were applied to the two different coppice types in order to determine the impacts on soil, while some differences between each type were determined by the site conditions. The silvicultural treatment applied was coppice with standards, aiming to guarantee a profit for the forest owner and to maintain an even-aged forest. For each area (described in Venanzi et al. (2016)), transects were examined in order to estimate that proportion impacted by machinery. Each transect was rectangular in shape (2 m x 50 m), laid crosswise to the maximum slope, making it possible to assess the percentage of the surface impacted by forest operations. In each forest, one random sampling plot (SP) per hectare was selected (18 for Turkey oak forest and 40 for chestnut forest) to determine: bulk density (BD), pH, organic matter content, penetration resistance (PR), and shear resistance (SR). Each SP was a circular area of 12 m in diameter, in which two different points (PO) were visually selected (e.g. based on the presence or absence of damaged understory, crushed litter, soil ruts or soil mixing) to represent disturbed or undisturbed soil conditions. To estimate the impact solely caused by the above ground removal of woody biomass (the silvicultural treatment, excluding the winching and skidding), it was compared with a control in a neighboring forest parcel which had remained undisturbed for over 10 years.

A QBS-ar analysis was carried out in each treatment by taking three soil core samples, each measuring 100 cm^2 and 10 cm deep. Microarthropods were extracted using a Berlese-Tüllgren funnel and the specimens were collected and identified to different taxonomic levels (class: Myriapoda; order: Insecta, Chelicerata and Crustacea). Soil quality was estimated with the QBS-ar index (Parisi et al. 2005; Gardi et al. 2008; Tabaglio et al. 2009;

Menta et al. 2010), based on the premise that the higher soil quality, the higher would be the expected number of microarthropod groups well adapted to soil habitats. Soil organisms were separated according to their morphological adaptation to soil environments; each of these forms is associated with an EMI score (eco-morphological index), which ranges from 1 to 20, according to the degree of adaptation. The QBS-ar index value is obtained from the EMI sum of all collected groups. The organisms belonging to each biological taxon were counted in order to estimate their density at the sampled depth and the ratio of the number of individuals and the sample area to 1 dm^2 of the surface.

RESULTS AND DISCUSSION

The proportion of forest surface impacted by logging operations is strictly related to the adequacy of the road network. In the coppices studied, the tractors skidded the trees on the forest floor only occasionally, and in these cases the impact was not only due to the amount of winching, but also the frequency of vehicle movements. The forest surface strongly impacted by forest operations ranged from 3.4% to 26.9% of the total area, showing a statistical difference between situations with good or inadequate forest trail networks. These results were notably lower than those obtained in other studies which had much higher densities of trees released after harvesting.

There were significant differences in bulk density, heavily influenced by both the silvicultural treatment and the impact by vehicles on the soil (Table 1 and Figure 1). Soil bulk density values were higher in the disturbed areas compared with undisturbed ones (average increase from 0.073 g/cm^3 to 0.209 g/cm^3, ranging from 10% to 27%). This was considered to be mainly the result of compaction caused by load transportation and in some cases vehicle traffic, but it affected only a low percentage of forest area. In comparison with the control (where there was no harvesting in the past decade), the BD in the undisturbed areas increased from 0.123 g/cm^3 to 0.210 g/cm^3, ranging from 19% to 39%. This was probably due to precipitation directly affecting the soil in all forest areas where above-ground biomass was removed.

Compared with the observations for bulk density, penetration resistances did not always show significantly greater values between the control and undisturbed areas, ranging from 0 to 0.06 MPa; 0-88%. However, the PR increased

Table 1. Results of the ANOVA and Tukey test for soil characteristics (average ± SD; letters show groups with statistically significant difference); differences tested between disturbed, undisturbed and control soil (Marchi et al. 2016; Venanzi et al. 2016)

Area	Soil typology	Bulk density [g/cm^3]	Penetration resistance [MPa]	Shear resistance [t/m^2]	Organic matter [%]	QBS-ar index
Quercus	Undisturbed	0.773±0.098a	0.128±0.05a	3.622±0.88a	13.5±1.85a	172a
	Disturbed	0.982±0.080b	0.294±0.09b	8.773±2.48b	11.1±2.20a	93b
	Control	0.650±0.101c	0.068±0.03c	2.544±0.74c	19.0±2.09b	251c
Castanea	Undisturbed	0.747±0.150a	0.066±0.011a	1.550±0.272a	18.1±1.3a	213a
	Disturbed	0.820±0.210b	0.276±0.090b	4.113±0.591b	13.1±1.6b	102b
	Control	0.537±0.110c	0.069±0.012a	1.569±0.310a	19.2±1.3a	198c

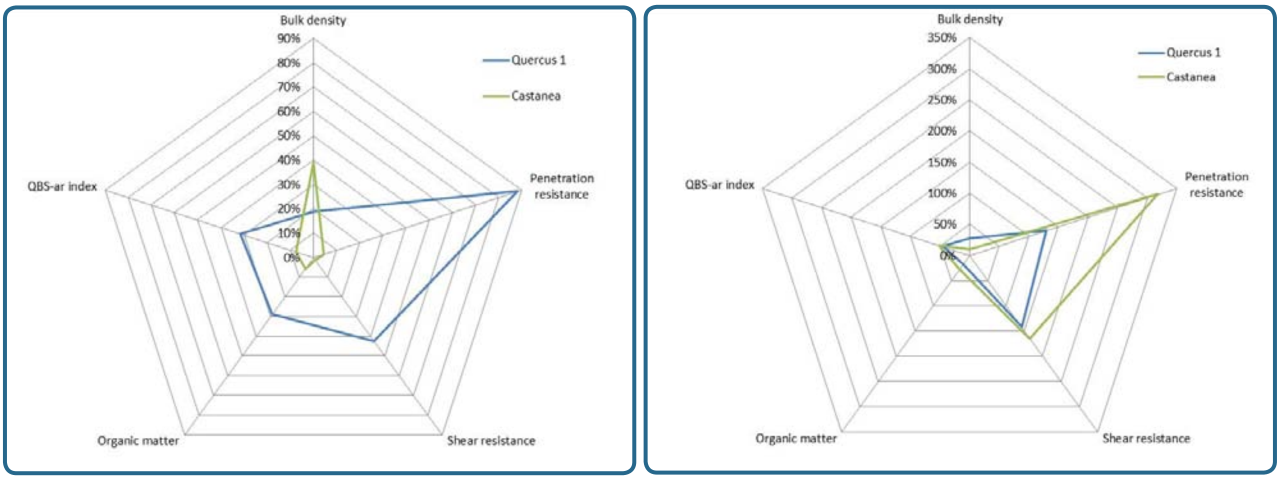

Figure 1. Percentage of impact for soil characteristics, on the left differences tested between undisturbed and control (silvicultural treatment) and on the right differences tested between undisturbed and disturbed soil (Marchi et al. 2016; Venanzi et al. 2016)

from 0.166 MPa to 0.210 MPa (ranging from +130% to +318%) when comparing disturbed and undisturbed areas. Similarly, while the soil shear resistance was not always greater in the control compared with the undisturbed areas (range from 0 to 1.08 t/m^2; 0-42%), in comparing disturbed and undisturbed areas, the SR increased from 2.56 to 5.15 t/m^2 (ranging from 142% to 165%). These relative differences among the three variables of bulk density and penetrometric and shear resistance showed similar significant trends, the greatest being for the latter two.

Soil organic matter content was also analyzed within the control site that had no utilization, and then within the forest areas harvested in this study. The organic matter content was lower in all areas affected by vehicle movements and from extracted loads. In chestnut coppice there was no significant statistical difference between areas undergoing harvesting (but not impacted by vehicles) compared with the control site. The areas disturbed by mechanical vehicle movement show a notable decrease in organic matter content, from 18 to 28%. This decrease can be linked to reduced mineralization as a result of less microbial activity in the disturbed area (Astolfi et al. 2011). Organic matter content was lower in all areas impacted by vehicles, while the removal of the above-ground woody biomass seems to only have caused significant change in Turkey oak coppice, at least during the first two years after the harvesting. Similarly, pH changes, which can influence many soil parameters and processes (Astolfi et al. 2011), did not seem to be affected by either the silvicultural treatment or the logging operations.

The QBS-ar index showed significant differences between the silvicultural treatment and the control, as well as between undisturbed and disturbed soils, indicating that the microarthropod community was affected in part by the silvicultural treatment and always by forest operations. Further analysis still in progress, two years after the treatment, shows that the QBS-ar index was lower than in the control within all of the areas directly involved with logging activities (temporary tracks), but that the recovery of the impacted soil was significant, but slow. From the same research in progress, the QBS-ar index was also affected by the silvicultural treatment, but in the soil surfaces not impacted by logging activities, recovery of the microarthropods was rapid. These results show that vehicle movement had a major impact on the soil condition, while the silvicultural treatment alone also had a clearly defined impact, but one that was recovered from quickly.

The QBS-ar index showed a high range of variation from disturbed to control areas (93–251 in Turkey oak, corresponding to a range of 8% to 52%), as was also observed by Blasi et al. (2013) and Rüdisser et al. (2015). In summary, the microarthropod communities were probably affected by the bunching and extraction operations of vehicle traffic and log dragging, causing soil compaction, while their density was similarly lower in all areas affected by vehicles and logging. Moreover, there was a statistically significant difference between the area subject to silvicultural treatment (but not impacted by vehicles) compared with the control site. In this case, however, it seems that the silvicultural treatment had a positive effect, perhaps related to an increase in soil nutrients immediately after the harvesting.

The QBS-ar can be considered a very useful qualitative indicator for coppice forests, as it is extremely sensitive to environmental variations caused by anthropic disturbance. This study has also shown that forest soil is extremely fragile in physical, as well as chemical and biological terms, and their highly complex interaction. Forest soils are extremely vulnerable to natural or anthropic disturbances, for example in logging operations (Vossbrink and Horn 2004). It is therefore extremely important that the impacts caused by forest management are quantified and the results used to design lower impact logging methods. These observations show that tractor tracks consistently cause compaction that can extend to a depth of at least 10 cm, creating a high risk of water runoff and wash out, which over time can cause a loss of fertile soil. Compacted soil can also impede seed germination, hinder regeneration and decrease forest productivity and continuity. Moreover, increased compaction causes a loss of soil micro- and macroporosity, reducing oxygen and moisture in the soil and drastically reducing micro-biological activity and fine root growth (Lynch et al. 2012). From a phytopathological viewpoint, increases in water runoff facilitate the expansion and transmission of pathogens as spores and rhizoids (Vannini et al. 2010). The overall consequence of soil compaction is a decrease of soil permeability, growth and nutrient supply to root systems. These negative consequences have also been shown by others (Heinonen et al. 2002; Alakukku 2000).

The coppice management system and the silvicultural treatment applied did not show any particular problems (i.e. in terms of seedling regeneration, fluctuations in seed production, prolonged periods of uncovered soil), but reduced impact logging (RIL) methodologies could be beneficial (Enters et al. 2002; Maesano et al. 2013). The logging operations in this case were carried out with appropriate mechanization, with tractors only skidding the trees on the forest floor occasionally, although physical-mechanical impacts caused by vehicle movement on forest soils (off the track) are evident even here. Carefully designed skid roads are therefore recommended, as well as setting out strip roads, skid trails and forwarder use so as to reduce soil disturbance. In future research, it would be interesting to evaluate the capacity for recovery from soil damage over longer periods of 2–16 years. For this specific study and other similar forest situations, if silvicultural treatments and logging activities are well planned and sustainable forest management guidelines were followed, no particular post-harvesting operations would be necessary. A forest road network that is viable and functional will further ensure a limited impact on forest soil, with impacted soil surfaces of <5–10%. It is important to consider the results of studies such as this one when compiling guidelines, criteria and indicators of sustainable forest management.

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Editors: Alicia Unrau, Gero Becker, Raffaele Spinelli, Dagnija Lazdina, Natascia Magagnotti, Valeriu-Norocel Nicolescu, Peter Buckley, Debbie Bartlett and Pieter D. Kofman

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