ANNALS OF SILVICULTURAL RESEARCH

Vol. 40 (2) - 2016

Consiglio per la ricerca in agricoltura
e l'analisi dell'economia agraria
Centro di ricerca per la Selvicoltura - Forestry Research Centre
Arezzo, Italy

ANNALS OF SILVICULTURAL RESEARCH
40 (2), 2016

http://ojs-cra.cilea.it/index.php/asr

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Review papers

Coppice forests, or the changeable aspect of things, a review[§]

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Received 15/09/2016 - Accepted 10/11/2016 - Published online 28/11/2016

Abstract - Coppiced forests were the main source of firewood, brushwood, and charcoal for rural and urban settlements' basic needs such as cooking food and domestic heating for thousands of years and up to the mid-20th century in many European countries and, specifically, in Mediterranean countries. The global diffusion of fossil fuels reduced this leadership and the coppice system turned, to some extent, to a reminder of the past. Nowadays, the ongoing global changes and the related green-economy issues call for resilient systems and effective bio-energy producers. These issues have caused a second turning point and the coppice has returned fifty years later to play a role. A review of the silvicultural system has been carried out with a special focus on the changes which have occurred in between, taking Italy as a consistent case-study. The analysis is mainly framed upon the long-term research trials established by the CREA-Forestry Research Centre in the late sixties, to find out adaptive management strategies and overcome the system's crisis. The findings and further knowledge achieved so far on the dynamics and functioning of coppice forests in the outgrown phase, both as natural evolutive patterns and silviculture-driven processes, are highlighted in this paper. They provide useful tools to handle the management shift regarding forthcoming issues, i.e. the current role attributable to the coppice system within the changing environment and the renewable energy demand. The basic features of each management area and their complementarities within the current framework are outlined.

Keywords - silvicultural system, natural dynamics, pro-active silviculture, sustainability, past management, future forestry, Italy

Foreword

Coppices have imprinted the broad-leaved forest landscape across Europe since the establishment of early human settlements. Coppice is an anthropogenic system created and optimised for small-sized wood production over several million hectares. The main products; firewood and charcoal, have had a global use because they assisted people's common, daily needs such as cooking food and domestic heating, whilst manufacturing produced a further, huge demand for energy over the last centuries. The peak of coppice exploitation took place during the first industrial revolution whilst its role reduced following the diffusion of fossil fuels since the mid-1900's.

Coppice forests are a significant part of Europe's semi-natural forests (about 70%) (Forest Europe 2011), characterise the forest landscape of the five EU Mediterranean countries over about 8.5 million hectares (Morandini 1994), and cover more than 3.6 million hectares in Italy (Gasparini and Tabacchi 2011). Italian coppices account for almost 19% of the coppices in the EU28, which in turn represent 83% and 52% in the whole of Europe and at global level, respectively (UN/ECE-FAO 2000, Mairota et al. 2016a).

Coppice forests are therefore a significant element of forest landscapes throughout Europe. The landscape is an appropriate management unit because it considers the interrelatedness of component segments. The spatial heterogeneity made of a mosaic of structurally different forest patches, the presence of different age classes, and the implementation of contact or transition zones among contrasting ecosystems are all conditions that favour environmental variability and, therefore, biological diversity (Scarascia-Mugnozza et al. 2000).

Italy may be taken as a consistent case-study between the Mediterranean region and neighbouring continental countries because of its large coppice forest coverage, the diversity of growth environments, the number of tree species that exist, and the evidence of large changes which have occurred over the last two centuries. The fragmented forest ownership structure with many private (73%) small-sized forest holdings is also a common trait in Europe (Forest Europe 2011).

Cultivation techniques have been well-documented since the Middle Ages (Piussi 1980 and 1982, Szabo et al. 2015), but there is also evidence of the late conversion of wide, high forest areas into coppices between the 1800's and 1900's following the

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[§] Partly funded by LIFE14 ENV/IT/000514 www.futureforcoppices.eu

http://dx.doi.org/ 10.12899/asr-1286

rising energy demand due to the sharp population increase and the concurrent rapid development of manufacturing activity (Agnoletti 2003).

Today, the analysis of silvicultural systems according to modern 'sustainability criteria' cannot ignore the basic question of the long-lasting, primary demand-driven, role of the coppice forest. In addition, it is nearly always impossible to separate this intensive cultivation system from the manifold overlapping uses and misuses of soil and tree vegetation. In fact, coppices have not only been used for short rotation wood production, but have also been over-exploited and used for deadwood and litter removal, the collection of leafy branches for fodder, occasional intercropping following shoots harvesting, and for unregulated pasture (Piussi 2006, 2015). This means uncodified, widely-practised 'multiple use'. The archives of Tuscany farms (central Italy) highlight that two thousand years of coppicing did not reduce stools vitality and site quality in the absence of overlapping, invasive uses (Piussi and Stiavelli 1986, Piussi and Zanzi Sulli 1997). The common judgment of non-sustainable system, in the long run has been built, therefore, on the full integration of the manifold uses on the same ground rather than on the coppice system itself (Fabbio 2010). Other external pressures (e.g. wildfires and uncontrolled grazing) or sensitive environments (e.g. steep mountain sides, shallow soils, and harsh climate conditions) have contributed to, and many times have caused, the decay of site fertility and the complete erosion of forest texture (MEDCOP 1998, Fabbio et al. 2003). This is the why there is evidence today of a vast array of conditions, from the relict cover of scattered trees to dense, well-growing coppiced forests where their management has followed the basic rules and supplementary uses have been less intensive or lasting, or site quality has supported them. Driving forces, limiting factors, and feedbacks were the determinants of the co-evolutive pattern between land use and growth medium (Fabbio 2010).

The background between the 1800's and 1900's

In the 1800's and early 1900's, coppiced forests clearly depicted the pressure exerted by the increasing population density on the available natural resources. Total forest cover at country level underwent a significant reduction in the 40 years between 1868 and 1911 when first-time coppice system prevailed over high forest. The reasons for this were the doubling of the population during this period and the industry's energy requirements which were 85% (1861) of fuelwood and charcoal (Agnoletti 2002). The rising price of charcoal caused social problems in the early 1900's and Italy began to import it between 1906 and 1913. At this time nine-tenths of charcoal were used for cooking food. The city of Rome alone burnt up to 90 million kg per year in the course of World War II (Hippoliti 2001). The ratio between forest resources and the population only changed in the mid-1900's when firewood and charcoal supplied 11% of the country's energy requirements compared to 85% during the previous century. At this time, the coppice system took part in the major socio-economic shift of the modern era since the first industrial revolution (Fabbio 2004).


Large, vital stool in an outgrown beech forest aged 70 yrs (Tuscany).

Many factors contributed to coppice downgrading: first, the much decreased economic significance of firewood production and the related lower profitability of its harvesting; then, the less intensive practice of forestry because of the emerging societal demands other than wood production; and finally, the critical association of coppicing with an out-of-date, ecologically-incorrect forest management system. Thus, the coppice system progressively reduced its leading role and turned, to some extent, to a 'reminder of the past' (Amorini and Fabbio 1994).

The new frame of reference can be outlined as the change of the original ground hosting the common matrix of coppiced young stands into a variable texture of stand ages and structures, stand dynamics, and growing stocks. In Italy, the current

Table 1 - Coppice cover in Italy by main tree species and stand age (source: Gasparini and Tabacchi 2011, INFC *mod.*).

tree species	cover		stand age					
	ha	%	<20 years	%	20<years<40	%	>40 years	%
Fagus sylvatica	477225	13.0	7728	1.6	128513	26.9	340984	71.5
Castanea sativa	593242	16.2	91908	15.5	277709	46.8	223625	37.7
Carpinus b. e *Ostrya c.*	636662	17.4	85250	13.4	325034	51.1	226379	35,6.
Q robur, Q. petraea, Q.pubescens	534325	14.6	54256	10.2	241590	45.2	238479	44.6
Q. cerris	675532	18.4	124999	18.5	314835	46.6	235699	34.9
Q. ilex, Q. suber	372020	10.2	27241	7.3	146679	39.4	198099	53.2
other spp.	374137	10.2	81390	21.8	151169	40.4	141578	37.8
Total	*3663143*	*100*	*472772*	*100*	*1585529*	*100*	*1604843*	*100*

distribution of coppice forests with respect to stand age (Tab.1) (Gasparini and Tabacchi 2011 *mod.*) highlights that young stands represent less than 1/3 of mature coppices, which is quite similar to that of ‘ageing’ stands. This composite panorama includes the stands which are still managed, the outgrown stands, and the minority proportion of stands being converted into high forests, which are mainly under public ownership and located in the upper mountain belt (Amorini and Fabbio 1992, Fabbio et al. 1998a) .

Historical statistics on firewood harvesting (Hippoliti 2001, Pettenella 2002, Ciccarese et al. 2006, Pra and Pettenella 2016) (Fig.1) show a minimum exploitation in the mid-seventies, whilst the last official statistics available on domestic fellings (ISTAT 2011) are similar to 2004. According to Forest Europe (2015), the current felling rate as a percentage of Net Annual Increment in Italy is one of the lowest in Europe: 39.2% compared to 47.3% in France, 80.3% in Germany, and 55.5% in Spain (Pra and Pettenella 2016). Even if the internal consumption of firewood from forests is only a part of the total consumption of the wood biomass for energy in Italy, which is estimated to be equal to 21.20 Mt (range between 16.37 and 22.17 Mt according to Pra and Pettenella 2016) or 19 Mt (Ciccarese et al. 2012), the official statistics are heavily underestimated (Corona et al. 2007). The reasons for this are generally related to the cross-sectorial character and fragmentation of the market. The multiplicity of sources on the supply side and the presence of different sub-markets and final users on the demand side make the wood energy market complex to clearly define and quantify (Steierer 2007, SFC 2008 in Pra and Pettenella 2016).

Visual impact of customary, slope-oriented coppice harvesting on a mountainside (central Apennines).

Final harvesting in a coppice with standards (Turkey oak forest, Latium).

The increased rotation length has been induced by several reasons: the suspension of charcoal production, the improvement in chopping tools and hauling/processing machinery (Schweier et al. 2015) and, especially, by the opportunity to harvest higher stocks per unit area. Over the last decades, the much-increased differential between manpower

Thickness of a holm oak coppice forest close to the age of rotation. Growing space occupancy is quite full (Corsica).

The high mortality rate is a typical trait of the early outgrown phase (holm oak forest, Sardinia).

Turkey oak coppice under conversion into high forest (Tuscany).

costs (x80) and firewood costs (x16), even with higher (x4) manpower productivity for processing and logging, led to doubling rotations and reaching the optimal shoot size of 10-15 cm. This trend, as highlighted by Hippoliti in 2001, is today the consolidated operational principle ruling the practice of coppice forestry.

Concurrent reasons are gaining ground today for the following reasons: the awareness of the residual stock of fossil fuels, the evidence of the climate shift in progress, the need for pro-active mitigation, i.e. that resilient and efficient forest systems have to be managed effectively, the fulfillment of emerging green economy issues (Marchetti et al. 2014). All of these call for streamlined production processes in a time of environmental change and increased bio-energy demand. This is why the coppice system has returned to play a potential, prominent role within the forestry domain.

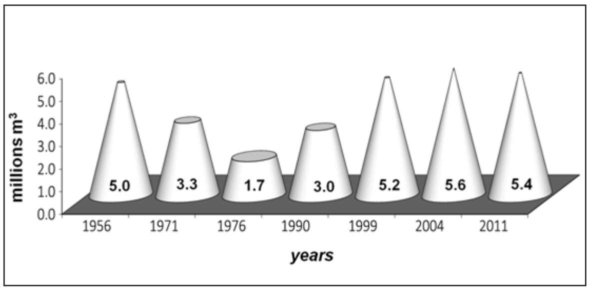


Figure 1 - Firewood harvesting over the last sixty years in Italy (2011, last official data available). (Sources: Hippoliti 2001, Pettenella 2002, Ciccarese et al. 2006 and 2012, Pra and Pettenella 2016).

This newly-established perspective leads, on the one hand, to the reconsideration of the legacy of the past, i.e. the fully tried techniques used for coppice systems; and on the other hand, calls for working hypotheses which are free of any subjective opinion other than ground-based evidence and the body of knowledge achieved so far.

The aim of this paper is to review the research questions which arose fifty years ago, the research pathway, and the main findings from the long-term research trials which have been established on this topic since the late sixties in Italy by the CREA - Forestry Research Centre. The main traits of the current scenario between the area managed under longer rotations, the outgrown area, the area undergoing conversion into high forest, and the role of each are outlined.

The need to handle the shift towards the suspension of harvesting/abandonment within a significant share of coppice area and to also suggest hypotheses for alternative, pro-active management has originated a series of applied research trials. These have compared the new options of coppice maintenance under the updated rules and/or conversion into high forest with the natural evolutive pattern or ‘outgrown phase’ in progress. These trials have contributed a better understanding of coppice system functioning above and below ground in terms of growth and re-growth ability, of dynamics and structure of the standing crop, as well as of the main drivers acting within each management choice.

The focus here is on the main tree species, i.e. the deciduous and evergreen oaks (Turkey oak, *Quercus cerris* L.; holm oak, *Quercus ilex* L.) and beech (*Fagus sylvatica* L.). Chestnut (*Castanea sativa* Mill.) was also considered in the trials but will be addressed in a next paper (Manetti, *forthcoming*) because of its peculiar traits with its set of available management options and the array of available wood assortments.

The research questions

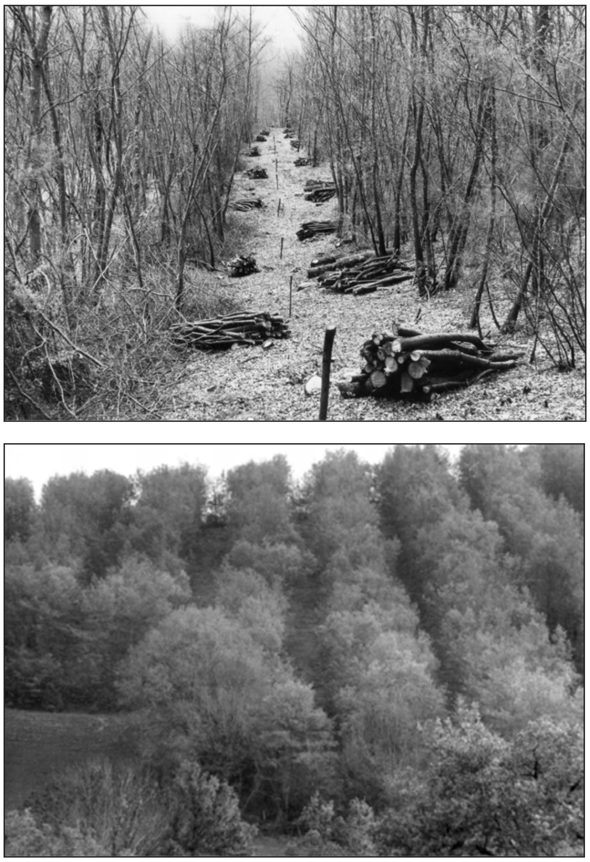
At the time the early papers on the subject-matter were issued (Gambi 1968, Guidi 1976, Amorini and Gambi 1977) and CREA’s first experimental trial was established (1969), a few basic questions were asked: (i) how could the share of coppice forests no longer being harvested be managed? (ii) what are coppiced forests’ growth patterns beyond the customary rotation? (iii) what is the decay rate of stools’ resprouting ability with stand ageing? (iv) what is the most suitable stand age to undertake coppice conversion into high forest and which practices should be implemented? (v) how can economic sustainability be achieved in order to tackle any pro-active silviculture, given that profitable firewood harvesting no longer exists? (vi) how can 'standards', i.e. the trees (usually from seed) released from one up to a few coppice rotations be managed?

The consolidated management cycles, which have been improved and finely tuned throughout centuries of cultivation, could not provide any answer to the above questions due to the ruling principles at that time. Rotations in use, well-grounded on the specific growth rate, were optimal for the: (i) size of harvested assortments (brushwood, charcoal, and fuelwood); (ii) cutting tools and the hauling techniques in use; (iii) avoidance of any yield loss due to the heavy competition among shoots and stools causing natural ('regular' according to Oliver and Larson 1996) mortality beyond customary rotations. Yield tables specific to coppice forests identified the rotations in use as close to the age of mean volume increment culmination, i.e. to the age of maximum wood production (Castellani 1982, see also Bernetti 1980).

The research pathway

The first CREA trials, established in the late 1960's when the suspension of harvesting was already in progress, basically compared the fairly unknown evolutive pattern of outgrown coppices and the alternative option of pro-active silviculture for coppice conversion into high forest. All of this may be seen as the establishment, ahead of its time, of an adaptive management approach. The following tools were used: the periodical survey of mensurational parameters, stem and root branches analyses, the analyses of tree layering set up and dynamics, and the shoots' mortality rate and progress survey. The collection of sample trees at the same sites allowed the measurement of dendrotypes within the consistent size-age span and the calculation of species-specific (beech, Turkey oak, holm oak) allometric functions (Amorini et al. 1995, Brandini and Tabacchi 1996, Amorini et al. 2000, Fabbio et al. 2002, Nocetti et al. 2007). Stem and root branches analyses made it possible to plot growth patterns from the coppice rotation up to the outgrown phase. These analyses were, therefore, a contribution to understanding the functions and processes already acting within the coppice cycle.

Further trials were implemented by the CREA within; the EU-Agrimed 'Multiple use of Mediterranean forests and prevention of forest fires' (1979-82) with an Italian-French partnership (Morandini 1979, Amorini et al. 1979), the EU-AIR2 'Improvement of Mediterranean coppices' MEDCOP (1994-98) involving the five EU Med. countries (Morandini 1994, Fabbio et al. 1998a), and the regional/national projects 'LIFE-Summacop' (Grohmann et al. 2002), 'TraSFoRM' (Amorini et al. 2002), 'RiSelvItalia'(2002-2004) (Fabbio 2004), ARSIA-Cedui (2004-06).



Agrimed (1979-82) 'Multiple use and prevention of forest fires'. Combined thinning method: opening of parallel clear-cut strips and selective thinning of standing crop (Turkey oak coppice forest, Tuscany).

Each project contributed to the establishment of further trials and analyses (Amorini et al. 1996, 1997, 1998ab, Fabbio 1994, Fabbio et al. 1996).

A basic entry within the newly-established research design was the 'adjusted coppice system' which was revised for average rotation length, harvesting, and thinning practices, the definition of 'standards' release (number, positioning, and aggregation on the ground), and the choice of the suited phenotype (Amorini et al. 1998c, Grohmann et al. 2002, Becagli et al. 2006, Cantiani et al. 2006, Savini 2010, Savini et al. 2015).

Further analyses addressed the parameters of productivity (litterfall, leaf area index), the canopy properties and the radiative climate (Cutini 1994ab, Cutini 1997, 2006, Cutini and Hajny 2006), the ecophysiological traits (Cutini and Mascia 1998, Cutini and Benvenuti 1998), the inner microclimate (Fabbio et al. 1998b), the dynamics of tree biomass and deadwood density (Bertini et al. 2010, 2012), and the stand structure and compositional diversity (Manetti and Gugliotta 2006, Manetti et al. 2013).

The theory and practice of silviculture according to the options in progress (Fabbio and Amorini 2006, Amorini et al. 2006), genetics and stand structure (Ducci et al. 2006), harvesting operations and hauling systems (Piegai and Fabiano 2006), technological improvement of wood assortments (Berti et al. 1998), biodiversity conservation (Baragatti et al. 2006), landscape analysis (Mairota et al. 2006), and the economic sustainability of the management systems (Fagarazzi et al. 2006) were the main subjects investigated within the mentioned projects.

The final points take into account the forthcoming issue of concern, i.e. analysing the resprouting ability of outgrown coppice stools. The issue is highly important if a share of the currently abandoned coppice area will be used for coppicing again.

The revision of practices ruling the customary technique of conversion to high forest has been tackled within the LIFE-ManForCBD (2010-2015). Innovative adaptive practices consisted of lowering symmetrical competition by reducing stand evenness to better address tree canopies for future regeneration by selective thinning. A case study was carried out in a beech stand under conversion to high forest (Fabbio et al. 2014). The advance seed cutting in the same forest type is addressed by Cutini et al. (2015), whilst long-term data on litter production, leaf area index, canopy transmittance, and growth efficiency estimates are again reported from a beech trial by Chianucci et al. (2016) .

Further contributions to the subject matter within the period of review are available in 'The improvement of Italian coppice forests' (Accademia Nazionale di Agricoltura 1979), 'Improvement of coppice forests in the Mediterranean region' (Morandini 1994), 'The coppice forest in Italy' (Ciancio and Nocentini eds. 2002), and 'The coppice forest. Silviculture, Regulation, Management' (Ciancio and Nocentini 2004).

The 'coppice issue' is also well-addressed by: the ongoing Cost Action FP1301 (EuroCoppice 2013 https://www.eurocoppice.uni-freiburg.de/) which aimed to develop the innovative management and multifunctional utilisation of traditional coppice forests and is an answer to future ecological, economic and social challenges in the European forestry sector; the international Conference held in Brno (Coppice 2015 http://coppice.eu/conference_en.html) where the past, present, and future of coppice forests were analysed alongside the new challenges in a changing environment; the LIFE FutureForCoppiceS (2015 http://www.futureforcoppices.eu/en/) which aimed to demonstrate the outcomes of different approaches by datasets collected from long-term experimental plots networks and improve the knowledge of Sustainable Forest Management indicators in view of the forecasted changes in key drivers and pressures.

The common goals addressed by these ongoing activities acknowledge the role of coppice system and the challenge for forestry within the newly-established economical and environmental conditions.

Main findings

Stand dynamics of outgrown coppice forests

The above ground process

In Italy, the available yield models for coppice forests date back to the 1940's up to the early 1980's (Tab.2). Predictive models set the age of 'maximum yield' or the 'age of mean annual volume increment culmination'. Scheduled rotations are quite short and vary as a function of the specific growth capacity and the site-index. The age of maximum yield often reported both for growing stock as a whole and for the firewood/brushwood component, underlines the attention paid to each harvestable assortment.

The evidence of incremental values higher than those recorded at the ages of previous rotations was provided by the repeated measurement of the standing crop volume and biomass undertaken since the establishment of the first permanent monitoring CREA sites in the late sixties (UNIF 1987). All of

Table 2 - Yield models for coppice forests in Italy (source: Castellani 1982).

main tree species	yield tables (years)	site class	stand age corresponding to the maximum yield (years)		
			growing stock	firewood	brushwood
Turkey oak	1948-49 to 1965-66	-	14-16		
	1950	I	9	12	
		II	9	12	
		III	12	12-15	
	1950	I		12	9
		II		12	9
	1966 to 1982	-		14	
holm oak	1963 to 1972	I	26-28		
		II	28	32	
		III	28		
beech	1947	I	17-18		
		II	16-22		
		III	18-23		

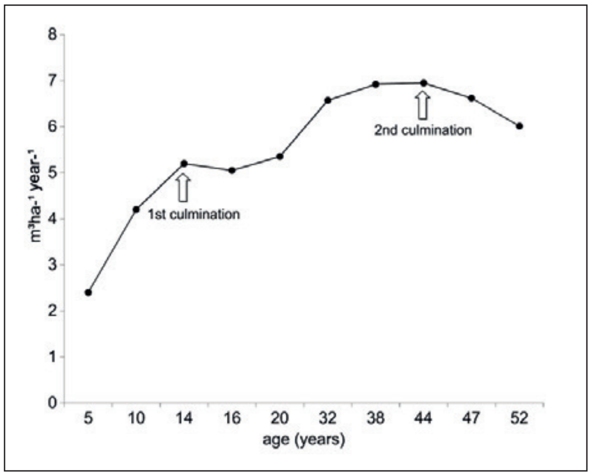


Figure 2 - Stand dynamics of an outgrown Turkey oak coppice forest: trend of mean annual volume increment.

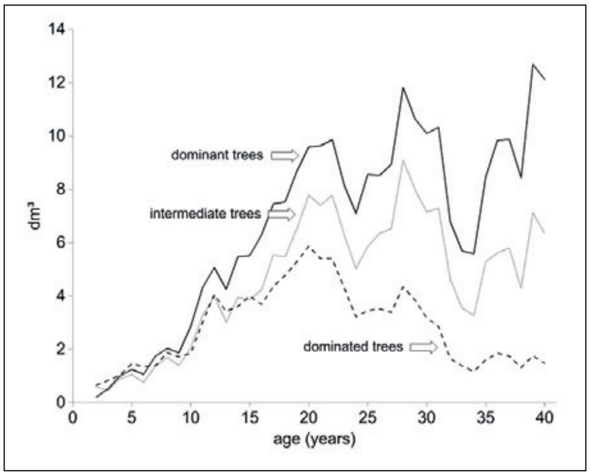


Figure 3 - Shoots dynamics of an outgrown Turkey oak coppice forest: averaged trend of current annual volume increment by the stem analysis per social ranks (same trial as in Fig. 2).

this occurred in spite of the heavier natural mortality rate recorded in between in the fully stocked outgrown coppices.

A second, higher culmination of mean annual volume increment was assessed for the first time in a 44-year-old Turkey oak coppice (Fig.2), much later than the first one (at the age of 14) as ruled by the yield models for the species (Amorini and Fabbio 1988). The same pattern was found to be common in the other stands investigated, i.e. beech and evergreen oak coppice forests (Amorini and Fabbio 1990).

This evidence clashed with previous literature and suggested further analyses. Stem analysis provided the ultimate answer to the matter. The analysis was carried out at the early-established trials on beech and Turkey oak in the Tuscan Apennines (Amorini and Fabbio 1986, 1989). The stratified tree sampling per growth layer (dominated, intermediate, and dominant) showed patterns made by synchronous current volume increment cycles in progress since the differentiation of ranks within the customary coppice rotation (Fig.3). The higher growth rate of the dominant shoots and the lower competitive ability of the not-dominant shoots over time were highlighted.

The current availability of a series of long-term monitoring trials allows the assessment of the growth dynamics in the outgrown (stored) coppice type between 44 and 75 years of age (Tab.3). The values show that growth culmination has already occurred at most sites, whilst the reduced difference of current to mean volume increment suggests that the peak is not far away at the other sites. Shade-tolerant species (holm oak, beech) show that growth culmination has not been reached yet between 60 and 75 years of age, with auto-ecology being the main driver.

What is, therefore, the meaning of the early culmination widely acknowledged by former yield models? It actually detects a first peak of growth shaped by the subsequent temporary steadiness due to the triggering of heavy competition among shoots and stools. It identifies the technical rotation suitable for small-sized wood harvesting, anticipates the occurrence of natural mortality, i.e. of any firewood production loss. It testifies the physiognomic evidence of the relative peak of growing space occupancy that takes place within the early rising stretch of the growth curve, but it is not the true culmination of stand growth from the current and mean volume increment patterns.

The unavailability of outgrown coppice forests up to the 1960's, the unfeasible checking of the temporariness of observed shoots' mortality and of the following growth recovery at the stand level, and

Table 3 - Assessment of growth pattern with reference to the age of maximum yield at the permanent sites monitored by CREA (*m.a.i.* = mean annual volume increment; *c.a.i.* = current annual volume increment).

main tree species	site	stand age (years)	c.a.i. $m^3ha^{-1}y^{-1}$	m.a.i. $m^3ha^{-1}y^{-1}$	m.a.i. = > c.a.i.
Turkey oak	Emi1*	60	2.8	4.0	*Yes*
	Laz1*	50	4.3	4.2	*close to*
	Mar1*	50	5.6	5.9	*Yes*
	Sic1*	65	3.0	3.5	*Yes*
	Vas	47	1.8	6.6	*Yes*
	Cas	55	3.6	7.5	*Yes*
	Pop	44	1.4	3.6	*Yes*
holm oak	Tos1*	65	3.8	4.0	*Yes*
	Tos2*	70	4.8	3.6	*No*
	Laz2*	65	5.5	3.5	*No*
	Sar1*	65	4.0	4.3	*Yes*
	Isc	55	0.9	4.1	*Yes*
beech	Emi2*	60	6.3	5.4	*No*
	Lom3*	60	9.0	5.7	*No*
	Pie1*	75	6.8	4.6	*No*
	Cat	67	6.5	7.5	*Yes*

* ICP- Forests Level II plots.

the already achieved firewood size are the likely, concurrent explanatory reasons for the general acceptance of traditional yield models (Amorini and Fabbio 2009). The evidence of further positive growth patterns supports well the current shifting of coppice rotations towards higher stand ages and large-sized firewood production.

Basal area growth rates from 1.4 - 1.9% up to 2.5 - 3.1% are being recorded in the deciduous/ evergreen oaks and beech outgrown coppice plots of the ICP intensive monitoring network in Italy (Fabbio et al. 2006a). Net primary production varies from 10.2 (Turkey oak) to 11.6 Mgha^{-1}y^{-1} (beech), whilst growth efficiency varies from 2.0 to 2.6, respectively.

A further index descriptive of growth patterns is the relative space occupancy calculated as the percentage ratio of shoots' standing biomass (standards excluded) to the volume defined by mean stand height per unit area (the proxy of the age-related growing space). The two case-studies (beech and Turkey oak) reported in Fig.4 describe species-specific patterns. The shade-tolerant species shows an early drop following the age of customary harvesting (24 years), and then the tendency is for a smooth increase until the end of the observed lifespan (67 years). The pattern of light-demanding oak maintains lower values throughout and has a nearly steady increase which reaches its culmination at the age of 44.

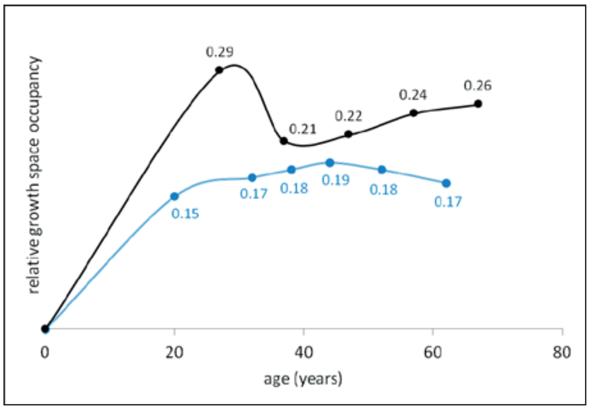


Figure 4 - Pattern of growing space occupancy by standing crop as a function of stand age in outgrown beech (black line) and Turkey oak (blue line) stands. Growing space occupancy is calculated as the relative ratio between standing crop volume and the theoretical available volume upper-bounded by the age-related mean stand height. Resprouting mass (shoots) is considered only. The small number of trees released since former cycles (the standards) at both stands makes them comparable.

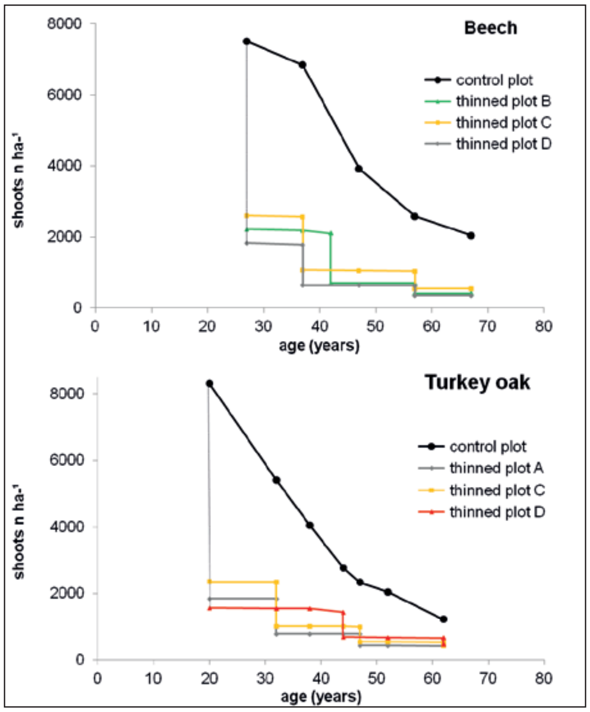


Figure 5 - Trend of shoots density at increasing stand ages at control and thinned plots in a beech and a Turkey oak outgrown coppice forest.

The pro-active practice of coppice conversion into high forest (Amorini and Gambi 1977, Fabbio and Amorini 2006, Amorini et al. 2006, 2010) allowed the comparison of this option to the outgrown phase within the same trials. The early, sharp drop in density at the first thinning and the much more reduced decreases following the intermediate harvestings are compared with natural tree mortality (Fig.5). Thinning to control densities are quite similar at the last age recorded in Turkey oak, whilst a marked difference is still present in beech plots, due to the specific shade-tolerance of the latter. The growth dynamics in terms of current and mean volume increment (Fig.6) in one beech (A) and two Turkey oak (B, C) experiments points out that management changes both incremental values and their course, whilst the age of culmination control vs. thinning remains nearly unchanged at each site. Beech stand shows a delayed age of culmination (60 years) as compared to Turkey oak. A marked difference exists between the Turkey oak sites: site B, located in the pre-Apennine range at an elevation of 700 m asl, showed the mean annual volume increment culmination close to 40 years, whilst site C, located close to the Thyrrenian coast at 200 m asl, culminates earlier, at about 30 years. There is also evidence of an abrupt drop in current annual volume increment following the culmination age at control plots.

Standing volume and standing volume plus intermediate harvestings (Tab.4) describe wood allotment at control and thinned plots, respectively. Intermediate yields suggest the economic feasibility within well-accessible sites and average production levels. Patterns of periodical thinnings aimed at promoting the recovery of the high forest physiognomy and triggering the sizing of final crop trees to better address the regeneration from seed are outlined (Fig.7). Intermediate harvestings show to be not negligible, even if the current wood destination is still firewood. The mean stand dbh throughout

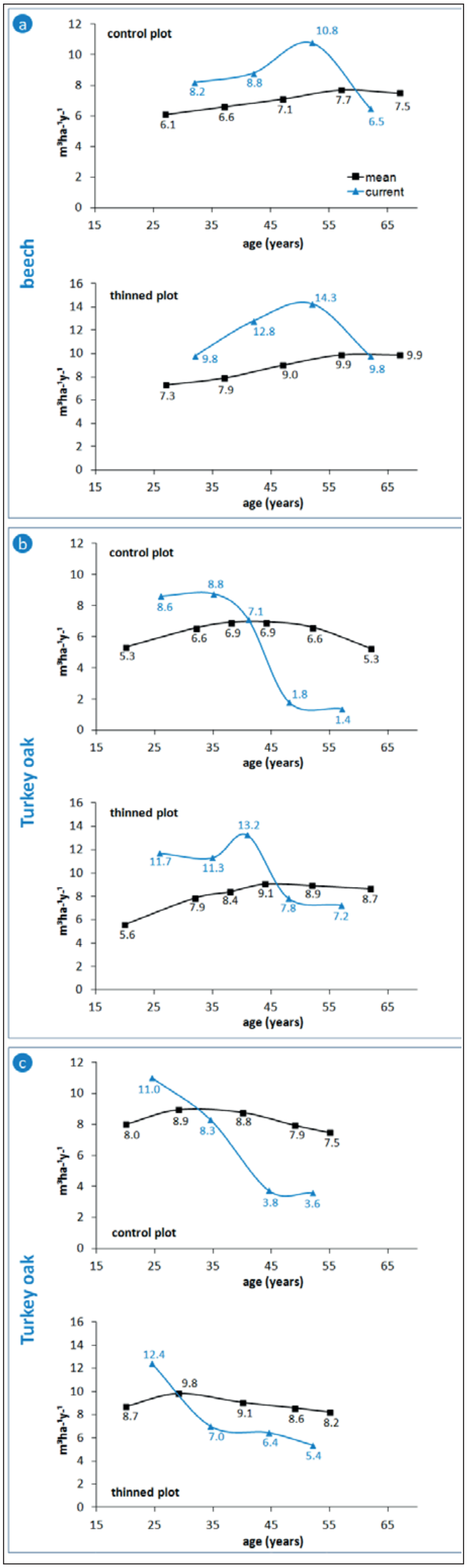


Figure 6 - Trends of current and mean volume increment of a beech (a) and Turkey oak (b, c) outgrown coppice forests at control and a thinned plot, respectively.

Table 4 - Dynamics of conversion to high forest vs. natural evolution (control plot). Current standing volume, intermediate and total yields at two permanent monitoring sites.

	BEECH (monitoring span = 27 - 67 years)		
treatment	**standing volume** m³ ha⁻¹	**Σ thinned volumes** m³ ha⁻¹	**total yield** m³ ha⁻¹
plots under conversion (average)	354	273 (3 thinnings)	627
control plot	505	-	505
	TURKEY OAK (monitoring span = 20 - 62 years)		
treatment	**standing volume** m³ ha⁻¹	**Σ thinned volumes** m³ ha⁻¹	**total yield** m³ ha⁻¹
plots under conversion (average)	287	215 (3 thinnings)	502
control plot	326	-	326

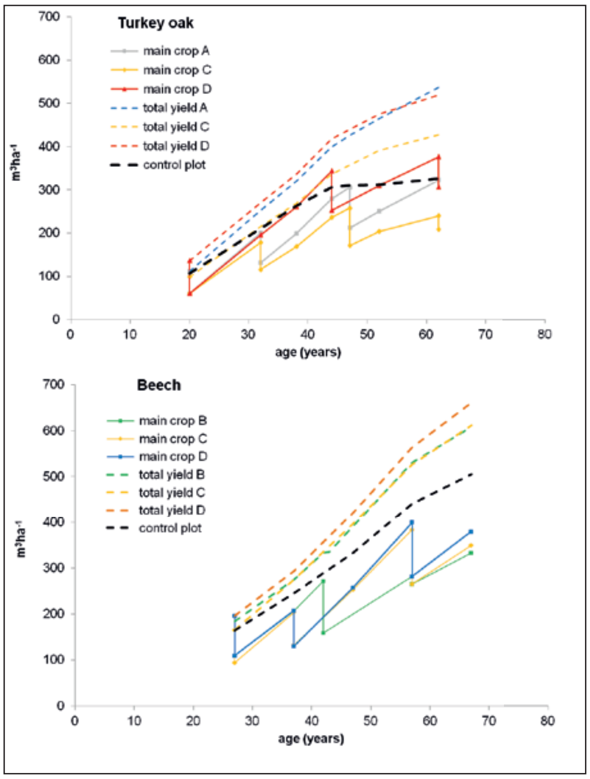


Figure 7 - Growth pattern of standing, main and total volumes at control plot and thinned plots in beech and Turkey oak outgrown coppice trials.

the explored life-span ranges from 9 to 34 cm (age 27-67 years) and from 9 to 26 cm (age 20-62 years) for beech and Turkey oak, respectively. The size of harvestable stems fits well and enhances the productivity of current handling-hauling systems.

The below ground process

The relationship between root system and above-ground biomass has a special significance in the coppice system since the prompt resprouting following the clear-cutting of stools in short time spans needs to be well supported belowground. A few hypotheses by Bernetti (1980, 1981) and Clauser (1981, 1998) regarding the development of outgrown coppice stands both in the above and underground components have produced original theoretical contributions. However, no field surveys and analyses studied the root system prior to the 1980's. A first digging trial was carried out (Fig.8-9) on a beech 'transitory crop', i.e. a coppice under conversion to high forest aged 43 years, thinned the first time at the age of 27 years, and the second time ten years later (at 37 years). The customary rotation was at 24. Therefore, the first thinning took place within the early establishment of the 'ageing period'. Two shoots were released at the first thinning and one at the second thinning on each of the sampled stools (Amorini et al. 1990).

Stem analysis was carried out for all living main (1st order) root branches (Fig.10). The age of each horizontal and vertical branch at the stool insertion, the annual radial increment, and the lengthening rate were determined. The shoot (stem) radial growth was also assessed at the height of 50 cm above ground level. Data refer to a stool living in the upper canopy layer, i.e. carrying at least one dominant shoot, which means a 'candidate' to be standing over the full conversion cycle. The results (Fig.11) apply to the time of coppice rotation (age 1-24 years) and to the transitory crop time (age 27-43 years).

- Horizontal rooting: only one living root aged before the last coppicing (1945) was detected; the new root branches sprouted as follows: +7 (age of 9), and +14 (age of 18). Three more branches sprouted before the first thinning, i.e. +17 in total (age of 27). No other branches developed over the transitory crop span (age > 27).
- Vertical rooting: no living branches aged more than the last coppicing were found. The development of new roots is slower in this sub-system +6 (age of 18), and +12 (age of 27). Only one new entry was detected within the transitory crop phase, i.e. +13 in total (age of 43).

At the age of survey (43 years), nearly all the main living root branches were developed after the last coppicing. This means that all the branches aged more, and still living during the last coppice cycle, ended their lifetime within the analysed time-span.

The resulting evidence of re-growth ability draws attention to the root system turnover as stool resprouting takes place after coppicing. These findings contribute a further understanding of stools' capacity to regrow several times without any depletion of their own regeneration potential. The same survey protocol, repeated a few years later in a Turkey oak ageing coppice, produced similar results.

Figure 8 - The digging trial of a beech coppice stool (1988).

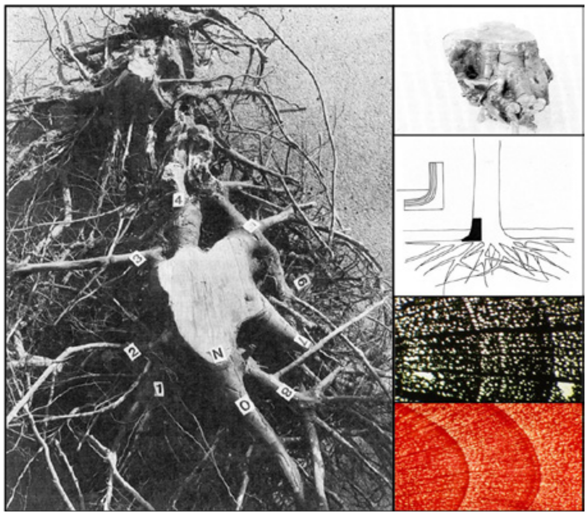


Figure 9 - Details of a beech root system.

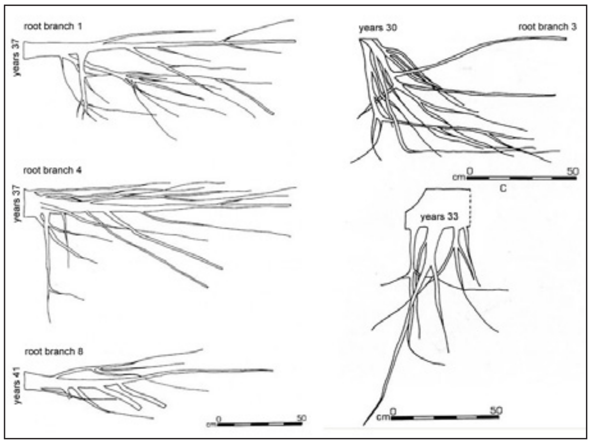


Figure 10 - Profile and age of main root branches at the insertion on the stool in a beech coppice.

An additional focus was on the development of the current radial increment at the shoot (stem) section at 50 cm above ground level and the total radial increment of the root branches measured at 10 cm from the stool insertion (Fig.12). The resulting patterns were quite similar over the full coppice cycle and also following each thinning in terms of reactive ability and growth rate. If the effect of growing space made available by the thinning on radial stem growth and crown sizing of released stems (the above ground component) was clear, there was

Root system mapping at digging out operations in a beech coppice stand (Tuscany).

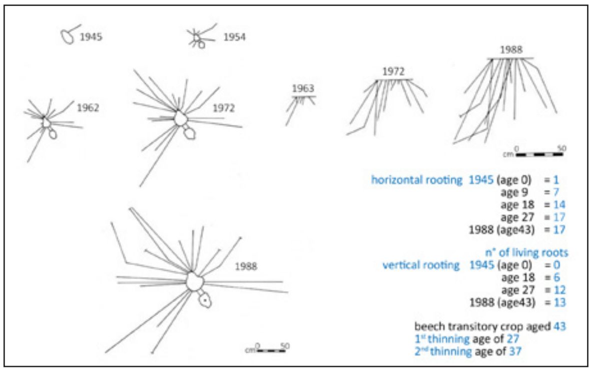


Figure 11 - Pattern of root branches development since last coppicing in a beech coppice. Age and number of living roots detected at the time of survey are reported.

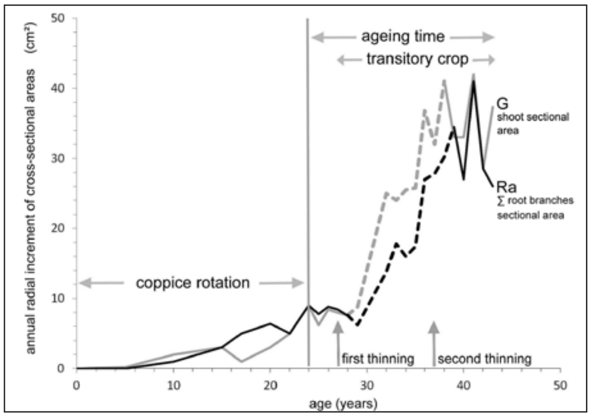


Figure 12 - Comparison between current radial increment (G) at the shoot section (height 50 cm) and total radial increment of root branches (ΣRa) at 10 cm from the stool insertion of a sampled stool in a beech coppice.

no evidence that a similar, synchronous reaction takes place below ground. The adaptive ability of the new-established root system fully accomplished the development of the above ground tree biomass according to a consistent functional significance.

This finding also helps the understanding of the fulfilment of trophic autonomy by the inherent regenerative ability hastened here by thinnings, drastically anticipating the reduction of the number of shoots on the stool by natural mortality.

Other attributes of relevance

Further evidence from the same sites stress the auto-ecology of main tree species as a principal driver in the outgrown coppice's lifetime. This trait rules the quantitative outcome of growth patterns. Shoots' mortality is anticipated in light-demanding species (e.g. Turkey oak) as compared with shade-tolerant species (e.g. beech) (Fig.13a) according to the average speed of variation (Odum 1973). The different behaviour is also highlighted by the contrasting trend of the 'auto-tolerance' or 'intra-specific competitive ability' (Zeide 2005) diverging from the ages of 45-50 years when a sharp increase occurs for the oak (i.e. a higher mortality rate under similar radial increment), whilst the competitive ability remains steady for beech (Fig. 13b). Further evidence of the auto-ecology – shade tolerance in this case – as the main driver of shoots' mortality is shown by the overlapping dbh distributions of standing dead shoots in outgrown beech and holm oak coppices aged likewise but living in quite different environments (Fig. 13c).

Clear proof of Zeide's statement 'shade tolerance affects the survival of trees but not their growth' (1985, 1991, 2005) is provided by shoots' radial increments in a beech outgrown coppice forest (Fig. 14a). One-quarter of living shoots (27%) is alive but no longer able to produce new tissue and its radial

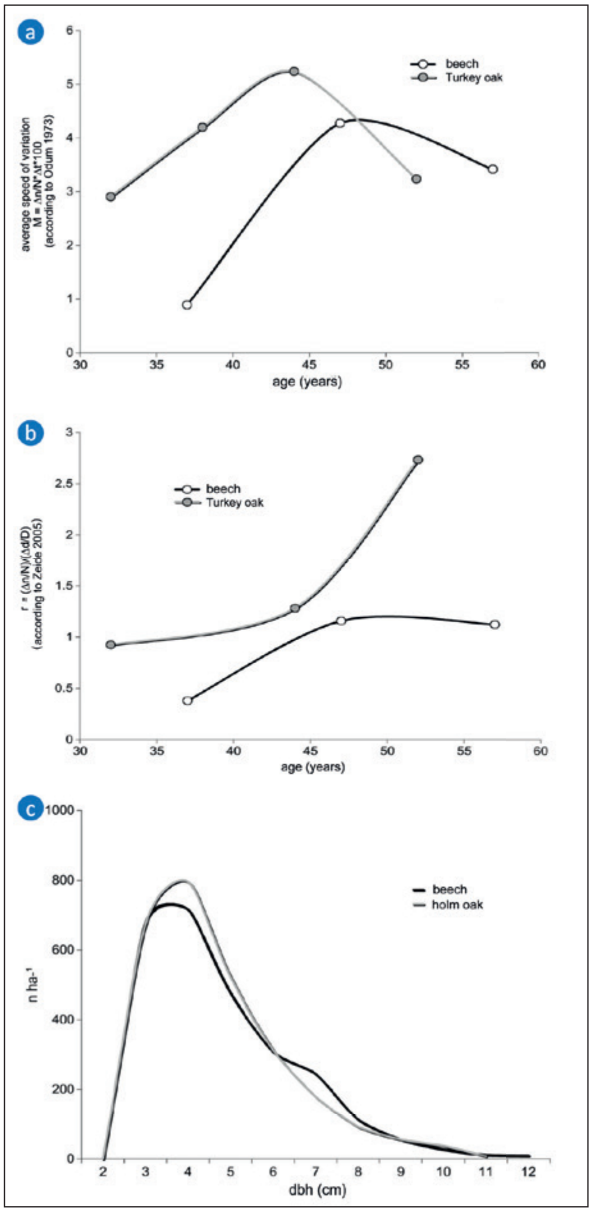


Figure13 - (a) Average speed of variation of shoots number in a shade-tolerant (beech) and a light-demanding tree species (Turkey oak) according to Odum (1973). (b) Trend of the 'auto-tolerance' or 'intra-specific competitive ability' according to the Zeide algorithm (2005). (c) Dbh frequency distributions of standing dead shoots in outgrown beech and holm oak coppices aged likewise.

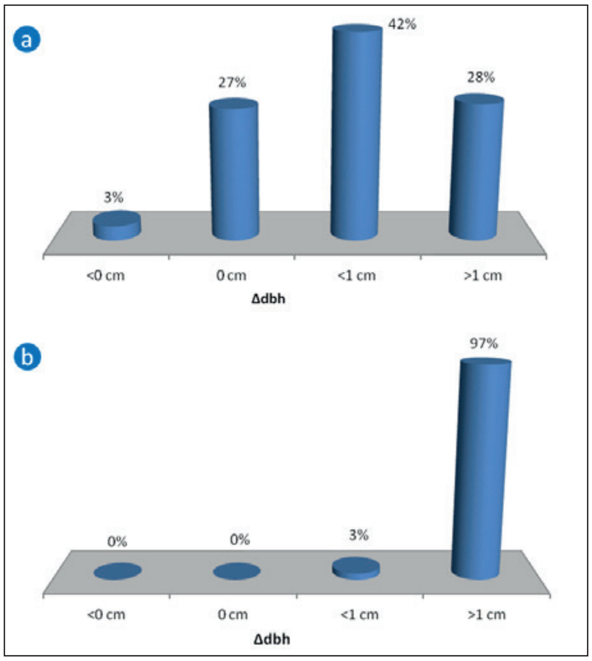


Figure 14 - Distribution of dbh growth under the natural evolutive pattern (control plot) (a) and in a thinned plot (b) within an outgrown beech coppice forest over the same life-span (age from 47 up to 57 years).

increment is zero within the not-negligible time span of ten years, whereas the standing dead population is only 3%. The quite different growth pattern within the same stand under conversion to high forest (Fig. 14b) highlights the change promoted by the repeated standing crop thinning causing a one-layered stand structure physiognomically similar to a pole stand from seed.

Tree biomass and standing/lying deadwood are complementary functional attributes along with stand age, especially in outgrown coppices. Their dynamics have a noticeable effect on deadwood accumulation on the forest floor. Tree biomass and standing/lying deadwood allocation for light-demanding (Turkey oak) and shade-tolerant (holm oak, beech) species are provided in Tab.5. The light-demanding species is characterised by the early shift of standing to lying deadwood ratio, whilst the opposite takes place for the shade-tolerant species. All of this is in spite of the quite similar mean

Table 5 - Standing shoots biomass, total, standing/lying deadwood, mean annual increments of standing biomass and deadwood according to stand age and main tree species.

main tree species	stand age	standing biomass	standing biomass mean annual increment	deadwood			standing to lying deadwood ratio	deadwood mean annual increment
				total	standing	lying		
	years	Mg ha^{-1}	Mg ha^{-1} year^{-1}	Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}		Mg ha^{-1} year^{-1}
Turkey oak	52	238.8	4.59	22.4	6.1	16.3	1/3	0.43
Turkey oak	55	313.0	5.69	30.0	9.8	20.2	1/2	0.55
holm oak	55	225.3	4.10	25.3	18.5	6.8	3/1	0.46
beech	57	321.6	5.64	27.7	19.5	8.2	2/1	0.49

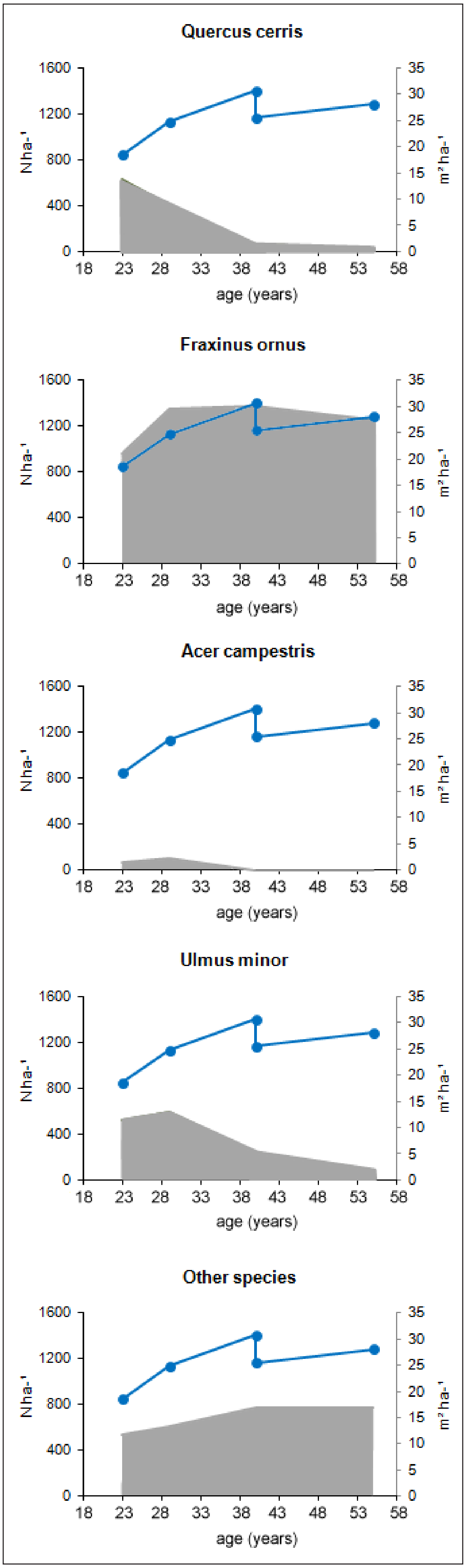


Figure 15 - Compositional diversity (number of trees per species = grey area) in the understory of a Turkey oak-dominated coppice under conversion to high forest and its change as a function of stand age and basal area in the main crop layer (blue line) used here as a proxy of upper canopy cover.

deadwood accumulation rate of about 0.5 Mgha^{-1} at all the sites (Bertini et al. 2010, 2012). This value ranges from 1/9 to 1/11 of the mean above ground biomass accumulation rate.

Also, compositional diversity follows different patterns under the same conditions according to specific ecological requirements. The presence-abundance and the time trend of complementary tree species living in the understory of a Turkey oak-dominated coppice under conversion into high forest are shown in Fig.15 (Fabbio and Amorini 2006).

Within the level II-ICP network in Italy, the outgrown coppice plots showed cases of dynamic-specific and structural stand rearrangement and among the highest values of tree richness (Fabbio et al. 2006b).

Another attribute relevant to the dynamics of coppice forests aged 40 to 60 years is the production of litterfall and leaf litter as compared with temperate-warm and temperate-cold forests (Fig.16). The ratio of leaf litter to total litter is about 70%; a typical figure for young, productive forests. In thinned stands, Leaf Area Index reduction to 4-5 optimises the Net Assimilation Rate and increases the Net Primary Production (Cutini and Hajny 2006). The amount of seed production and the frequency of mast years are species-specific traits. Turkey oak shows an annual production five times higher than beech on average (0.70 vs. 0.13 Mgha^{-1}), which is also due to the much more frequent occurrence of

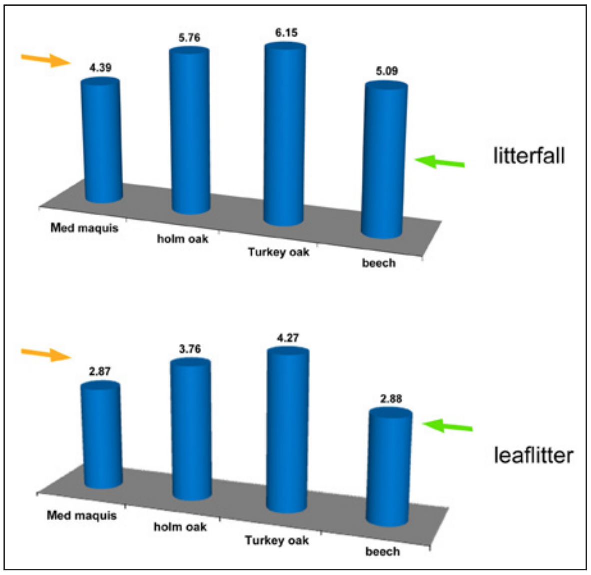


Figure 16 - Average litterfall and leaflitter production (Mgha^{-1}) in coppice stands aged 40 to 60. Arrows show the average for temperate-warm (left) and temperate-cold (right) forests (sources: Bray and Gorham 1964, O'Neil and De Angelis 1981, in Cutini and Hajny 2006).

mast years (Cutini 2000 and 2002). These attributes become of major concern at the time of stand regeneration from seed.

A paradox is finally evident if we account for the damage due to wildlife browsing on stools resprouting. The 86% of Turkey oak stools browsed the first year after coppicing did not survive over the following two years (Cantiani et al. 2006). An average reduction of standing volume up to 57% and 41% was determined six and eleven years after coppicing, respectively (Cutini et al. 2011). The issue is of even greater concern when it becomes the driver for the successful resprouting of outgrown coppice stools as reported by Pyttel (2015) for sessile oak stands aged 80-100 years. This 'modern' disturbance may be heavier than the past practice of grazing by domestic animals and is can compromise the whole wood production cycle. The issue at hand puts forward the critical question of wildlife conservation practice, i.e. protection or breeding?

The most recent research issues at the CREA trials dealt with: forest management and water use efficiency (Di Matteo et al. 2010), environment-induced specific adaptive traits and C and N pools by different compartments (Di Matteo et al. 2014ab), seed production patterns (Cutini et al. 2010, 2013), management of the final phase of conversion into high forest, i.e. the implementation of regeneration cuttings (Cutini et al. 2015), the long-term response of coppice conversion to high forest experiments (Chianucci et al. 2016) and, again, the wildlife browsing impact on stools' resprouting (Chianucci et al. 2015).

Main traits and role of the management areas established on the former coppice cover

Land use and land use change

The original coppice system area underwent a significant reduction some fifty years ago. Land use and land use change are consistent with the dynamics of social and economic context. Both originate from factual needs and when the related commodities can be usefully replaced, produced elsewhere or the customary use is no longer profitable, land use is abandoned (Del Favero 2000) or changed (Mottet et al. 2006). Other spontaneous or man-induced changes have taken place in the landscape matrix since the time of coppice abandonment on less accessible and less fertile sites. The natural afforestation of open areas (abandoned fields and rangelands) contributed to the steady increase of forest-type cover, reduced the patchy distribution of open areas and homogenized the forest cover over the last decades. The establishment of agro-forestry systems and, more recently, of short rotation forestry on lands set aside by the agricultural practice have modified the human-imprinted landscape. The newly-established tree farming created further interfaces between rural and urban areas on the plains or hilly sites no longer favourable for agriculture, but fertile enough and with good access with respect to intensive wood production. This sequence contributes recent traits of landscape dynamics. Our perception of land use is first supported and consolidated by the long-lasting direct, visual/physiognomic experience and then transferred by documental sources. This is the way a common 'heritage' value is established over generations.

If the balance between practice and its profitability and/or replaceability historically dictated land use, the modern acknowledgement of complementary societal benefits arising from its maintenance can move, to some extent, the point of balance. In this case, the community should reward the fulfilment of shared common benefits and contribute to the feasibility of the use in concern. This seems to be the basic condition for answering some questions. Reference is made to the manifold calls for coppice recovery as a heritage value or the driver of 'bio-cultural diversity' (Burgi 2015) where it was historically present, but independently of its current, profitable implementation. Also, the frequently asked question about the evidence of vegetational and faunal diversity loss (Kopecky et al. 2015, Vild et al. 2013, Mullerova 2015ab) being closely linked to the short-term opening of patchy clearings in the forest cover as in the former coppice system (Kirby 2015) should be settled within the same frame of reference.

The area managed under the coppice system

Easily-accessible areas to make profitable wood harvesting, good site fertility allowing sustained growth and closeness to the market are the basic requirements for effective management of today's coppice system. The updating of management criteria includes: (i) lengthening customary rotations, (ii) recovery of technical function for 'standards' release (i.e. reducing their number, effective selection of dendrotypes, and suitable spatial arrangement), (iii) obtaining certified productions, and (iv) search for the optimal size, shape and contiguity of clearings according to the different physical environments.

The main purpose of maintaining a coppice system is still firewood production, but there are other complementary benefits such as the contribution to the landscape mosaic texture providing specific habitats, types, and patterns of diversity (Mairota et al. 2014, Burgi 2015, Hédl et al. 2015) which is also linked to the early successional stages inside the clearings (Kirby 2015).

The emerging green economy issues (Marchetti et al. 2014), the structural change from a fossil-based economy to a bio-based economy (Corona 2014), and the increased demand for renewable energy resources may be the turning point which addresses the forthcoming role of coppice forests. Positive factors remain the basic attributes of the system, i.e. the easy management technique, the guarantee of natural regeneration, the flexibility/reversibility, and the resistance/resilience. In this regard, the adaptability of oak coppice forests to changed conditions, namely water management, is reported by Splichalova (2015), whilst the higher drought tolerance of sessile oak resproutings vs. seedlings under soil moisture limiting conditions is underlined by Holisova et al. (2015) and Pietras et al. (2016). It is also worth recalling that resprouting ability has been one of the most important keys to the building up of the paradigm of resilience and post-disturbance auto-successional nature of Mediterranean coppice forests (Espelta et al. 1999, Konstantinidis et al. 2006, in Lopez et al. 2009).

The more manageable length of stand lifespan compared with the high forest system widens the options for handling the risk and unpredictability of climate shift in the primary phase (regeneration) and throughout the forest cycle.

Further concurrent elements today are the chance to select contexts optimal to cultivation within the former coppice area, the reduced impact of historical overlapping uses, the reasonable less intensive management ruling the system, the improved knowledge achieved so far about the bio-ecological functioning (drivers, limiting factors, and feedbacks), the above and below-ground dynamics, and the growth patterns.


Final harvesting: the irregular shape of the cutting areas edge results in a lower visual impact even in case of large clearings (northern Apennines).

Special focus is being developed and consistent techniques are applied to the effective tending of valuable, even sporadic tree species within coppice stands (Pelleri, *this paper*).

Besides all its positive traits, coppice remains a low-input, high-output energy system compared to other silvicultural systems because of the natural assurance of crop regeneration. This is why, looking back but ahead too, a consistent definition of coppice may be today ‘a very ancient but modern system as well’ (Fabbio 2015).

Conservation and enhancement of sporadic tree species living in coppice forests: the CREA experience

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‘Sporadic tree species’ means trees living both as individuals and small groups within a forest stand; they are often able to produce quality timber, and valuable broadleaved tree species are included within this category (Mori et al. 2007). Following the ageing of unmanaged coppice stands and the customary practices of conversion into high forest, the progressive reduction of sporadic tree species is usually recorded, since most of sporadic tree species are less competitive than dominant tree species (Mori and Pelleri 2012). Because of their attributes (light-demanding, poorly competitive, reduced growth), such species are very sensitive to any practice going to change stand structure parameters. Their maintenance and increase in value runs through practices targeted to complying with their auto-ecology. The tree-oriented silviculture, an approach developed in central Europe for oak, beech and spruce high forests (Abetz 1993, Sevrin 1994, Bastien and Wilhelm 2000, Abetz and Kladtke 2002, Wilhelm 2003), especially fits both conservation and enhancement of sporadic tree species in coppice forests (Spiecker 2006, Spiecker et al. 2009, Sansone et al. 2012, Pelleri et al. 2013 and 2015, Manetti et al. 2016).

Appropriate fields of application
The economically feasible and successful practice of tree-oriented silviculture in coppice forests is based on the selection of a limited number of suitable trees as for vigour, stem quality and crown quality. Prerequisites are the presence of these dendrotypes, well-accessible sites, favourable ecological conditions. Under these assumptions, tree-oriented silviculture can ensure the persistence of these species, their natural regeneration and the increase of valuable timber production. Thinnings localized around a limited number of selected trees allows to manage the remaining standing crop as in the customary way, without reducing noticeably the firewood production of the coppice system (Sansone et al. 2012, Mori and Pelleri 2014).

This approach was recently applied within the LIFE-PProSpoT in coppice forests in central Tuscany on an overall area of 53 hectares. Ten to twenty target trees per hectare were promoted by localized crown thinning to get their free crown expansion. Trials were undertaken both in young and ageing coppice stands.

The young coppice stands

The enforcement of tree-oriented silviculture in stands aged 10-15 years allows the conservation of compositional diversity, as well as the promotion of growth pattern and timber value of the selected trees. A notable increase of radial increment from 1-2 up to 5-7 mm per year has been reached in a few years in service tree and wild service tree, whilst the growth rate has increased from 2-4 up to 8-10 mm per year in field maple. Stem diameter increment similar or higher can be achieved by field elm and wild cherry (Wilhelm e Ducos 1996, Nicolescu et al. 2009, Manetti et al. 2016, Giuliarelli et al. 2016).

The maintenance of these growth rates implies heavy crown thinnings repeated every 6-8 years to get the crown release of 2-3 m, or less intense (1-2 m of crown release) but more frequent thinnings (4-6 years).

The ageing coppice stands

Practices are aimed at favouring more the conservation and fruiting of sporadic valuable tree species, whilst less achievable is the increase in value of wood production. Light-demanding species are especially unable to react to late thinnings (service tree, European ash, wild cherry, peduncolate oak, etc.), whilst the reaction ability is more evident for shade-tolerant species (wild service tree, linden, sycamore, holly tree, etc.) even in the late life-span; these are less-sensitive to tree competition and maintain a more deep and efficient crown, just able to react also to late openings (Rasmussen 2007).


Wild service target tree in a mixed coppice forest aged 15 years.


Wild cherry target tree in a chestnut coppice stand aged 16 years before thinning.

The 'standards' release

At coppicing, it is advisable to protect the young selected trees with a belt of shoots (grouped standards release) to avoid any damage due to the sudden isolation (stem quality worsening, e.g. growth of epicormic branches or stem breakage). Large-sized sporadic trees provided with well-developed crowns may be released as individuals without any significant risk. The grouping of standards may be supplemented by the customary release of individuals of the main and sporadic tree species (Mori and Pelleri 2014).

The use of the proposed tending techniques may result in the successful maintenance and improvement of wood production value as well as in the preservation of a higher compositional diversity.

The post-cultivation area or the outgrown coppice stands

Outgrown coppice stands are widespread under marginal conditions in terms of accessibility and site quality, but they are also widespread in public-owned areas and in areas designated for nature conservation. Here, main forest functions are the soil protection or its recovery, the re-establishment of habitats similar to those former to human-imprinting, the carbon stock and sequestration (mitigation), the contribution to landscape texture, and the maintenance of specific habitats for biodiversity conservation. Small-scale silvicultural practices should be introduced to allow the maintenance of target tree species, stand structural and compositional diversity into the abandoned mosaic-like structures where protection is also a target issue (Garbarino et al. 2015, Urbinati et al. 2015). New adaptive rules allowing the coexistence of gamic and agamic regeneration in the same stand have been recently introduced in northern Italy (Motta et al. 2015).

The increased forest area under different protection levels, the enforced regulations heavily limiting or making difficult the implementation of any form of management for wood production – independently of bio-ecological conditions and site location suitable for harvesting – have contributed to the unmanaged coppice area increasing. Hence, forests also susceptible to still being under sustainable coppice system rules but included in areas protected today as a whole, are not effectively manageable (Mairota et al. 2016b). Due to this conservative position, a non-defined permanence time of stands and minimal interventions addressed to promote seed regeneration are foreseeable at now.

A point of concern is provided by the high amount of standing and lying woody necromass in these overstocked types making them very sensitive to fire. This issue has to be taken into account by managers of large, continuous forest covers within environments prone to wildfire occurrence (Corona et al. 2015).

The coppicing of aged crops provides case studies of utmost importance in order to collect grounded evidence about the long-term resprouting capacity of stools. An inventory of these cases and their analysis would be the main source of knowledge for the time being. It might provide, in addition to the very few trials established in between, the necessary expertise to again undertake coppicing under suitable conditions, to meet the renewable bio-energy demand, and reduce the unmanaged areas.

Suitable conditions mean the occurrence of: (i) geomorphological and soil attributes allowing repeated clearcutting even with doubled rotation lengths, (ii) good site quality for sustained and sustainable firewood production, and (iii) well-accessible locations allowing the reduction of harvesting costs.

The area under conversion into high forest

The main goal of the conversion of coppice into high forest is to anticipate the recovery of former high forest structure managing timely the outgrown coppice crops. The choice is consistent with sites fertile enough and stand textures sufficiently dense to get the awaited outcome within the conversion cycle. The periodic revenues from thinnings make this option economically enforceable to different sizes and types of ownership. The presence of valuable, even sporadic, tree species is an added value here.

Less relevant in terms of total area, this option has special significance in the public domain, where a share of the wide forest cover which is no longer harvested is available to a pro-active, adaptive silviculture. The decision to undertake such silviculture should be pursued according to a few, logical steps. The mountain areas, where the coppice system has been suspended earlier because of lower profitability and higher environmental sensitivity, should be taken into account first. Then, the areas which are valuable because of tree-specific composition and of scenic value, or under-targeted conservation, may be included in this option. Management rules are the tending practices applied to standing crops up to their regeneration from seed (Amorini and Fabbio 1990, 1994, 2009, Alberti et al. 2015). Adaptive strategies may be usefully added to the thinning methods in use to implement a higher canopy differentiation of standing crops already in the second half of the conversion cycle. This implies the selective tending of best phenotypes to favour individual crown development and to reduce the evenness of the one-storied stands (Fabbio et al. 2014).

The main purpose of this choice remains a more suitable balance between wood, non-wood productions, and environmental functions as in the

Harvested coppice area a few years after coppicing. The irregular shape of clear-cut makes easier the physiognomical re-establishment within surrounding texture (holm oak forest, southern Italy).

traits of the high forest system. It implies a more extended lifetime and the implementation of the intermediate set of silvicultural practices ensuring the awaited growth pattern of the selected shoots in the main crop layer as well as their health and vitality throughout the conversion cycle and up to the regeneration from seed.

Conclusive remarks

Each management type which has arisen from the common coppice matrix shows peculiar and consolidated features. All of them have become established as a result of factual macro-economic conditions and provide a range of goods and benefits. They basically run according to different management criteria, intensity, and the type of applied practices up to post-cultivation. Further inherent or practice-driven dynamics will be determined by criteria prevailing at the multiple decision-making levels and by changing scenarios as well (Millar et al. 2007, Lindner et al. 2010).

Stakeholders, planners, and managers should envisage all the available options and their possible connections on the ground as well as their complementarities in landscape planning.

They should also acknowledge the consistency of each choice according to the prevailing local function(s), the site quality, and the bio-ecological conditions at the operational scales of silviculture and forest management, i.e. from the stand up to the forest compartment level.

This rationale accomplishes and supports many, already well-achieved, statements. Among these, worthy of mention are: [...] the establishment and mosaic of the different choices builds up the organic development of land matrix and its connections (Franklin 1993); [...] intensive to extensive cultivation systems up to pure conservation tailored at the local scale may coexist and implement diverse development stages and structural diversity from stand up to landscape level (Fuhrer 2000, Farrell et al. 2000); [...] the complex and varied physical context allows post-cultivation and pro-active management approaches as well, both of them being strategic and complementary (Di Castri 1996, Teissier Du Cros 2001, Palmberg-Lerche 2001, Fabbio et al. 2003).

The forthcoming challenge will be the tuning of management strategies so they are able to make the system function effectively under the new condition(s). Two main open questions remain for coppice forests as for any other biological system living within a changing growth medium. Are we moving from a steady state to a perennial transition? Furthermore, how much of the inherent ecological buffer has been/will be eroded in between?

Acknowledgements

I am grateful to Francesco Pelleri for contributing his own specific expertise to the subject-matter.

I also want to thank here several of my colleagues who have been and are working on trials on coppice forests at our Institute: Germano Gambi, Giulio Guidi, Riccardo Morandini, Emilio Amorini, Maria Chiara Manetti, Andrea Cutini, Paolo Cantiani, Francesco Pelleri, Silvano Ghetti, Vittorio Mattioli, Dino Gialli, Nevio Donati, Luigi Mencacci, Umberto Cerofolini, Mario Romani, Galeazzo Scaioli, Mauro Frattegiani, Silvia Bruschini, Claudia Benvenuti, Maurizio Piovosi, Giada Bertini, Claudia Becagli, Tessa Giannini, Luca Marchino, Walter Cresti, Eligio Bucchioni, and Leonardo Tonveronachi.

Finally, a special thank you goes to Germano Gambi and Emilio Amorini who first introduced me to the subject matter and to the CREA trials on coppice forests.

1988, the digging trial.

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Annals of Silvicultural Research
40 (2), 2016: 133-139

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Research papers

Factors affecting branch wound occlusion and associated decay following pruning - a case study with wild cherry (*Prunus avium* L.)

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Received 08/04/2016 - Accepted 27/10/2016 - Published online 28/11/2016

Abstract - Pruning wild cherry (*Prunus avium* L.) is a common silvicultural practice carried out to produce valuable timber at a veneer wood quality. Sub-optimal pruning treatments can permit un-occluded pruning wounds to develop devaluing decay. The aim of this study is to determine relevant branch, tree and pruning characteristics affecting the occlusion process of pruning wounds. Important factors influencing occlusion time for an optimised pruning treatment for valuable timber production utilising wild cherry are derived. 85 artificially pruned branches originating from ten wild cherry trees were retrospectively analysed. Branch stub length, branch diameter and radial stem increment during occlusion were found to be significant predictors for occlusion time. From the results it could be concluded that for the long term success of artificial pruning of wild cherry it is crucial to (*i*) keep branch stubs short (while avoiding damage to the branch collar), (*ii*) to enable the tree to maintain significant radial growth after pruning, (*iii*) to avoid large pruning wounds (>2.5 cm) by removing steeply angled and fast growing branches at an early stage.

Keywords - high value timber production, wound occlusion, stub occlusion

Introduction

Modern forestry management should simultaneously satisfy ecological, economical and social demands of both the public and of forest owners. Valuable broadleaf tree species can be especially regarded as an option to fulfil the multidimensional requirements of today's forestry sector, where an economic return is crucial. The inclusion of valuable broadleaves can also simultaneously increase biodiversity and aesthetics within forests and agricultural land (Rapey 1994, Dupraz 1994, Bell 2009).

High value logs destined for veneer must meet a number of quality parameters: large diameter, cylindrical shaft forms, high volume of knotless wood, a uniform colour and an absence of decay (Mahler 1988, Spiecker 2003, Kupka 2007, Springmann et al. 2011a). Large dimensioned high quality logs with a small knotty core reach the highest prices. The reduction of the width of the occlusion zone to a minimum in order to harvest greater amounts of branch free timber is one important goal for silvicultural management. This goal requires timely and repeated interventions especially in juvenile stages. Of particular importance is artificial pruning in order to reach the production target of branch free valuable timber (Balandier 1997, Oosterban et al. 2009). This is especially true for open grown trees (Balandier and Dupraz 1999) where natural pruning occurs to a lesser extent. The same is true for tree species that do not self prune well (Röhrig et al. 2006). Both points are relevant for wild cherry (*Prunus avium* L.) cultivated in widely spaced systems.

Wild cherry is often considered to be a valuable broadleaved species yielding high prices under relatively short rotations (Bulfin and Radford 1998, Balandier and Dupraz 1999, Morhart et al. 2014). In order to obtain a high quality product, artificial pruning is of upmost necessity (Otter 1954, Balandier and Dupraz 1999, Thies et al. 2009, Springmann et al. 2011b). This results in a small dimensioned knotty core surrounded by branch free wood. The longer it takes for a pruning wound to occlude the larger the knotty core becomes. Therefore, in order to maximise clear wood, the time taken for complete branch stub occlusion must be minimised. The influencing factors for occlusion time and their effects play an important role for silvicultural management. Pruning operations undertaken in conifer stands have been the subject of much research (Møller 1960, Långström and Hellqvist 1991, O'Hara and Buckland 1996) while studies centred around hardwood species are less frequent (Kerr and Morgan 2006, Hein and Spiecker 2007, Dănescu et al. 2015). Previous research conducted on ash (*Fraxinus excelsior* L.) and sycamore (*Acer pseudoplatanus* L.) by Hein and Spiecker (2007) and Dănescu et al.

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http://dx.doi.org/10.12899/asr-1193

(2015) could identify significant effects presented by branch diameter and radial increment during the time of wound occlusion. Current literature advises that branch diameters of wild cherry at the time of pruning should not exceed 3.0 cm at the branch collar (Pryor 1988, Spiecker and Spiecker 1988, Seifert et al. 2010, Springmann et al. 2011b). Additionally, the quality of the pruning cut, as expressed by the roughness of the cut surface and the length of the remaining stub is believed to have an effect on occlusion time (Dujesiefken et al. 1998, Springmann et al. 2011b).

Pruning methods such as selective pruning (Spiecker 2010, Springmann et al. 2011b) can improve the production of veneer quality timber from wild cherry due to the early removal of the most vital branches. This results in smaller branch diameter of the pruned branches, and hence, smaller pruning wounds. An employment of this method means that occlusion time should be reduced, which in turn implies a lesser risk of infection of the pruning wound (Spiecker 2010) by wood decaying fungi such as *Phellinus tuberculosus* Baumg. and *Trametes* spp. (Seifert et al. 2010). Hence, the first objective of this study is to evaluate the influence of different parameters such as branch-stub length, branch diameter, radial growth, insertion angle of the branch and cardinal direction on the occlusion time of pruned branches. The second objective was to reveal how branch diameter and occlusion time influence the development of wood decay.

Materials & Methods

The 2.5 ha experimental site is located on the floodplain of the river Rhine in south western Germany close to the town of Breisach (48.071N; 7.589E, 182 m a.s.l.) situated on former agricultural land. The soils are not considered deficient in essential minerals and nutrients. A detailed description of the site, soils and climate conditions can be found in Morhart et al. (2016). The site and climatic conditions can be considered suitable for the growth of wild cherry. The site index for pruned cherry is described as class II: a tree height of 26.7 m at an age of 60 years is to be expected according to applicable yield tables (Spiecker 1994).

The research site was planted in 1997 with 1+1 wild cherry stock derived from the Liliental seed orchard, established within a randomised block design. The initial spacing of all trees on the research plot was 1.5 m x 7.5 m and 1.5 m x 15.0 m in a mixture with other broadleaves species including European ash, pedunculate oak (*Quercus. robur* L.), sycamore, small-leaved lime (*Tilia cordata* Mill.) and European hornbeam (*Carpinus betulus* L.). This mixture relates to the site's aim of investigating the growth of valuable broadleaved tree species within a widely spaced planting design. Thinning was carried out to favour future crop trees, i.e. those displaying a high radial increment and suitable form.

In 2015 a total of 10 wild cherry classified as dominant and co-dominant trees (Kraft 1884) were sampled. These trees were artificially pruned in three year intervals (2007, 2010 and 2013), thus, reflecting representative crop tree management practices. After felling the trees, each whorl was carefully examined for partially or fully occluded branches and the respective whorls were sampled. This yielded 63 occluded and 22 partially occluded artificially pruned branches for further analyses. In addition stem discs were taken for retrospective radial increment analysis at 1.3 m, 2.5 m, 5.0 m and 7.5 m from the ground.

Samples were air-dried under ventilated conditions for three weeks before being prepared for examination. Branch whorls were cut parallel to the stem axis so that the included branches could be divided centrally (see Fig.1 left).

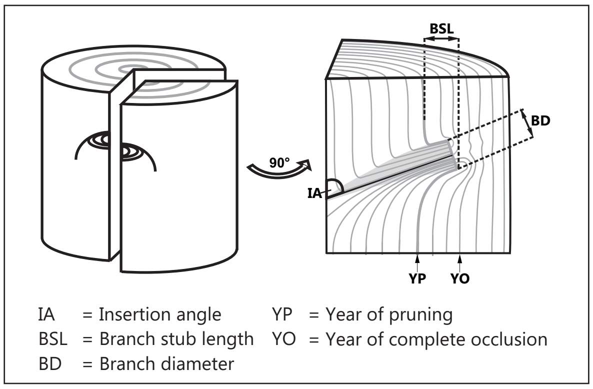

Figure 1 - Measured parameters within sampled whorl sections.

All cut surfaces, plus the stem discs, were sanded with 240 grit sandpaper to prepare them for further analyses. Cardinal direction (CD) of the occluded branches was measured in respect to a north datum that was marked in the field. Tree ring width, as a proxy for radial increment during pruning wound occlusion, was measured on all stem discs, using the software WinDENDRO TM (Regent Instruments Inc.). The yearly quadratic mean radial increment during occlusion was calculated from four orthogonal radii.

For determination of occlusion time (*OT*), the year of pruning (*YP*) and the year of complete occlusion (*YO*) were established (*OT* = *YO* – *YP*). *YP* was defined as the last year in which a defined tree ring originates in the stem and converges within the branch, while *YO* was identified as the first defect free tree ring entirely covering the pruning wound.

The branch cross sectional diameter (*BD*) at the site of the cut face, and the insertion angle (*IA*) of the pruned branch were additionally measured. To obtain the best possible measurement of IA, 50% of BD was utilised as a point of measurement with the vertex of the angle located where the branch pith met the stem pith. Branch stub length (*BSL*) was measured on the underside of the branch using the distance between *YP* and the lower lip of the pruning cut. All measurement sites are illustrated within Fig. 1. To determine the radial increment during the time of wound occlusion (*irO*) we used the yearly quadratic mean radial increment of the stem disc that was located closest to the pruned branch.

Investigation of stem decay as a result of artificial pruning is based on data derived from a total of 85 branches, 63 of which were completely occluded and 22 that remained un occluded, In order to retrospectively investigate stem decay associated with fungal infection, branches were first visually sampled for signs of decay. Three levels of decay were defined: No visible wood decay, wood decay limited to the pruned branch (Level I) and wood decay spreading through the pruned branch into the stem wood (Level II).

Statistical analysis and modelling

Data analysis was carried out using SPSS for Windows 22.0 software (IBM Corp. 2013). The level of significance was set at $p = 0.05$ for all analyses. Normality was tested with a Shapiro-Wilk test. Stepwise ordinary least squares regression was performed to model branch occlusion time as a consequence of *BD*, *irO*, *BSL*, *IA* and *CD*. The independent predictor variables were included within the model in a stepwise method ensuring significance. Residuals were assessed for homoscedasticity by visual analysis of the studentised residuals plotted against predicted values and a normal distribution was ensured using normal Q-Q plots. A Durbin-Watson test was carried out to assess whether there was autocorrelation between residuals and the Variance Inflation Factor (VIF) evaluated in order to assess multicolliniarity within the model. The Akaike Information Criterion (AIC) was utilised to reinforce the choice of model (values can be seen in Tab. 2). The derived model followed the form of Eq. 1 where *OT* is pruning wound occlusion time (years) and X the respective independent predictor variables with associated beta values (β) as derived from the regression analysis.

$$OT = \beta_0 + \beta_1 \mathrm{X}_1 + \beta_2 \mathrm{X}_2 \ldots \beta_p \mathrm{X}_\mathrm{p} \qquad \text{Eq. 1}$$

Results

The following data were attained from 63 completely occluded and 22 non occluded pruned branches.

Tab. 1 displays descriptive statistics for the parameters measured for all fully occluded branches within the sample (n=63). Occlusion time ranged between two and seven years, branch diameter was measured between 7.0 mm and 40.0 mm, branch stub length presented a maximum length of 25.0 mm within the sample while branch radial increment growth ranged between 1.60 mm/year to 4.59 mm/year for fast growing branches. *BSL*, *BD* and *irO* all proved to significantly contribute to the model and hence, model III (F(3,59) = 14.4, p=<0.001) was chosen providing the best model fit and lowest AIC value (see Tab. 2).

Table 1 - Descriptive statistics for occlusion time (*OT*), branch diameter (*BD*), radial increment during occlusion (*irO*), branch stub length (*BSL*) and insertion angle (*IA*) for completely occluded branches (n=63).

Variable	Min.	Max.	Mean.	S.D.
OT (years)	2.0	7.0	4.3	1.2
BD (cm)	0.7	4.0	1.9	0.7
irO (mm)	1.6	4.6	3.0	0.8
BSL (cm)	0.0	2.5	0.6	0.7
IA (°)	31.0	86.0	53.7	12.2

Table 2 - Model parameters for the prediction of wound occlusion time (*OT*) utilising branch stub length (*BSL*), branch diameter (BD) and radial increment during occlusion (*irO*) as predictor variables (n=63).

Model	Included Variables	F	df	R	r^2_{adj}	p	AIC
I	*BSL*	27.5	1,61	0.557	0.299	<0.001	-0.978
II	*BSL, BD*	17.7	2,60	0.609	0.350	<0.001	-4.789
III	*BSL, BD, irO*	14.4	3,59	0.650	0.394	<0.001	-8.223

Table 3 - Regression parameters of model III for the prediction of wound occlusion time (*OT*) utilising branch stub length (*BSL*), branch diameter (*BD*) and radial increment during occlusion (*irO*) as predictor variables (n=63), where β is the beta coefficient and Se the standard error.

Var.	β	Se	*p*-Value	Partial r²	Structure Coefficients
Constant	4.206	0.595	<0.001	---	---
BSL	0.818	0.174	<0.001	0.22	0.857
BD	0.352	0.149	0.0214	0.05	0.315
irO	-0.350	0.152	0.0247	0.05	-0.632

The model was statistically significant and accounts for approximately 40% of the variance of pruned branch occlusion time ($r^2_{adj} = 0.394$). Partial r^2 values suggest that BSL provides the backbone of the model (22%) with *BD* and *irO* supporting with 5% respectively. This is also supported by the stated structure coefficients also given in Tab. 3. Both *IA* (p=0.239) and *CD* (p= 0.277) did not contribute significantly to the model and were, therefore, excluded.

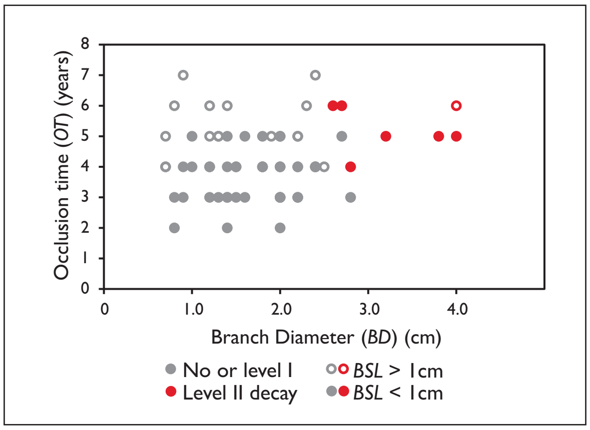

Figure 2 - Occlusion time (*OT*) as a function of branch diameter (*BD*) with marker types indicating branch stub length (*BSL*). Level II decay is indicated by red markers (n=63).

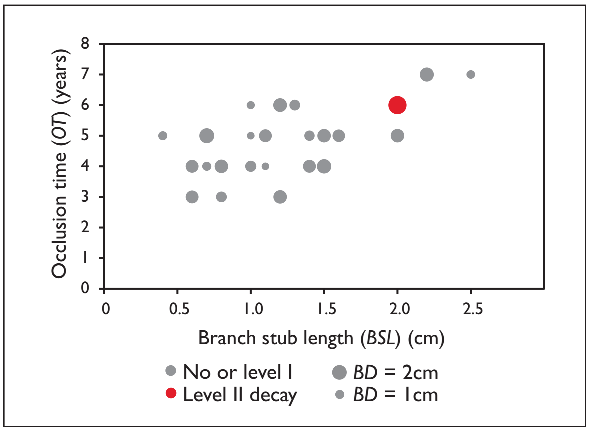

Figure 3 - Occlusion time (*OT*) as a function of branch stub length (*BSL*) (n=30). Size of the markers corresponds to branch diameter (*BD*), size of data points are proportional to branch diameter. Level II decay is indicated in red.

To visually demonstrate the influence of *BD*, *BSL* and *irO* as important contributing factors affecting *OT* Fig. 2, Fig. 3 and Fig. 4 are presented. Fig. 2 shows occlusion time against branches of different diameters. A significant increase (p=0.021) in occlusion time related to increasing branch diameter can be observed. The pruning of larger branches, thus, results in an extension of the time of wound occlusion. It can be seen that even small branches of less than 1.0 cm in diameter can take up to seven years to be completely occluded. Such long occlusion times for small diameter branches can be attributed to other factors such as the *BSL* (Fig. 2 *BSL* > 1.0 cm shown with unfilled points) and the *irO*. *OT* for pruning wounds with a *BSL* of more than 1.0 cm in length is significantly longer (p=0.001) than that for branch stubs shorter than 1.0 cm. Fig. 3 illustrates the correlation between occlusion time and branch stub length with longer branch stubs resulting in a significant (p<0.001) prolongation of occlusion time, irrespective of branch diameter. Fig. 4 exhibits the relationship between occlusion time and radial increment during the period of wound occlusion, where a significant negative correlation (p=0.025) can be observed.

From the sampled branch stubs 89% of fully occluded branches show no decay or decay classed as level I, while 50% of surveyed branches which have not fully occluded after eight or more years show a decay of level II. 18% of un-occluded branches showed no symptoms of decay at the time of analysis. A Kruskal-Wallis H test showed that the distribution of occlusion time as a function of *BD*, *BSL* and *irO* between decay levels is not the same ($\chi^2(2)$ = 22.248, p = <0.001). mean rank scores of 31.03, 43.29 and 64.39 were calculated for no decay, decay level I and decay level II respectively. Fig. 5 illustrates the correlation between the occurrence of decay in artificially pruned branches and the duration of wound occlusion. Pruning wounds that are completely occluded within two to three years exhibit negligible amounts of level I decay and none of the 17 branches in that category could be diagnosed with severe stem decay (level II). If complete occlusion takes up to four years, a large increase (55% of studied branches) of decay within the pruned branches can be observed. Occlusion times of four years and beyond show the first occurrences of severe stem decay, spreading through the pruning wound in an axial direction into the stem wood. Analysis of Fig. 5 suggests that if the pruning wound takes up to five years to be completely occluded almost 20% of the branches will exhibit decay at level II. While at six years and above there are 19% of branches that are completely unaffected by wood decay while 45% are severely infected by level II decay.

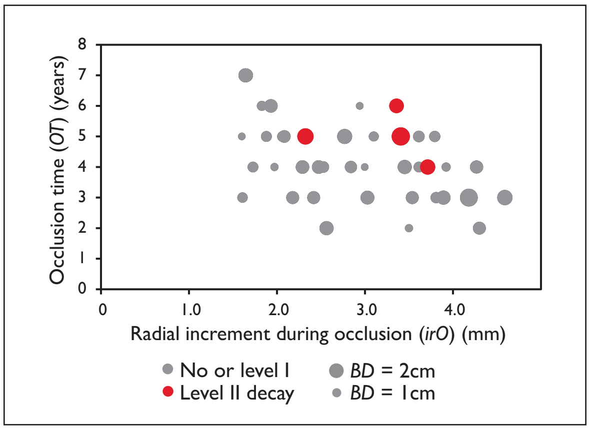

Figure 4 - Occlusion time (*OT*) as a function of radial increment during occlusion (*irO*) (n=63). Size of the markers corresponds to branch diameter (*BD*), size of data points are proportional to branch diameter. Level II decay is indicated in red.

To examine the correlation between the formation of decay and branch diameter we investigated those branches that were pruned with a *BSL* of less than 0.5 cm. This way we could include branches that had been pruned with a correct cut peripheral

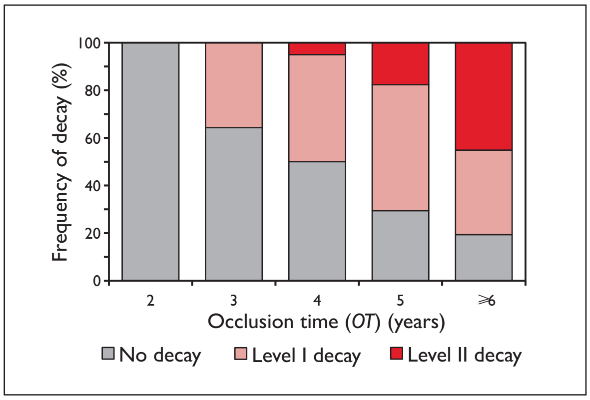

Figure 5 - Percentage frequency of the three levels of decay following artificial pruning (n=85).

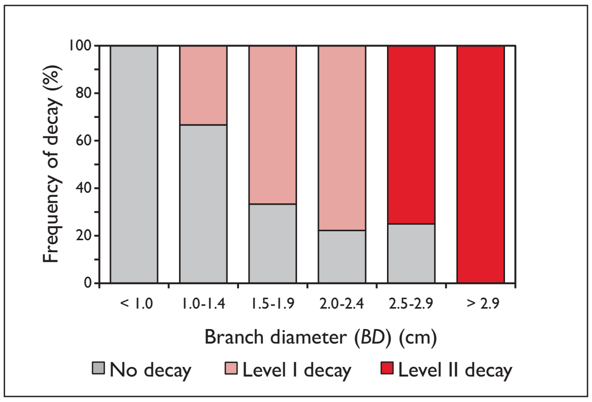

Figure 6 - Percentage frequency of the three levels of decay following artificial pruning for different branch diameters with BSL <0.5 cm (n=34).

to the branch collar. Stubs resulting from the existence of a branch collar never exceeded 0.5 cm in all samples. By setting this threshold we eliminated the large influence of *BSL* on occlusion time which results from poor pruning cuts to be able to assess the occurrence of decay for arising from pruning cuts that follow best practice. This limited the sample size to 34 branches. The correlation between pruned branch diameter and the occurrence of wood decay is illustrated in Fig. 6. Level I decay can be observed with increasing branch diameters starting in the diameter range from 1.0 to 1.5 cm. About 40% of the 22 sampled branches in the diameter range from 1.0 to 2.5 cm exhibit level I decay. Severe stem decay (i.e. level II) can be found commencing at pruned branch diameters of 2.5 cm with 85% of pruned branches showing axial spread of decay into the stem wood.

Discussion

This article retrospectively investigates the occlusion of pruning wounds on wild cherry trees. The impact of different stub parameters such as branch diameter, stub length or branch insertion angle in relation to the bole on the occlusion zone was analysed. It was shown that increased radial increment within the stem results in a reduction in occlusion time, i.e. fast growing trees occlude pruning wounds faster, a logical conclusion. Occlusion time is delayed by an increase in the diameter of pruned branches and by the increased length of the remaining branch stub.

Modelled results suggest that branch stub length, branch diameter and radial increment of the stem during the time of occlusion are all significant predictors of pruned branch occlusion time with a standard error of the estimate of 0.9 years.

The largest contributory factor towards a fast occlusion time is branch stub length, a consequence of the accuracy of pruning operations. Within the model *BSL* contributed 22% of the total for the explanation of variance. This variable has a larger effect on the duration of wound occlusion than the diameter of the branch itself or the radial increment of the stem during the occlusion period. Multiple studies found similar relations in various conifer and broadleaved tree species (Anderson 1951, Finnis 1953, O'Hara and Buckland 1996, Metzler 1997, Dănescu et al. 2015). It could be shown that the majority of fully occluded branches presented a pruned branch stub <1.0 cm. Such pruning wounds were occluded within two to five years dependent on the rate of radial increment within the stem. A recommendation suggesting that branch stubs are a maximum of 1 cm in length constitutes clear easy to follow advice for the practitioner. Nevertheless, an optimal pruning cut should be made close to the bole, as longer branch stubs will significantly extend occlusion time, and therefore, increase the risk of severe stem decay. However, care must be taken not to cut into the branch collar if present (Springmann et al. 2011a). Correct pruning practice must be carried out by making the cut adjacent to the outer perimeter of a branch collar.

These finding concur with current literature: Hein (2003) explicitly suggests the elimination of long branch stubs as one of the key advantages of artificial pruning compared to natural pruning in ash and sycamore, since the wound occlusion time is significantly shortened. Petruncio et al. (1997), utilising a stepwise regression method in order to model branch occlusion in coastal Douglas fir (*Pseudotsuga menziesii* var. menziesii [Mirb.] Franco), concluded that total occlusion time increases with large diameter stem sections (whorl diameter), with long branch stubs and if branches are dead at the time of pruning.

Results of the regression suggest that branch diameter contributes 5% towards the explanation of wound occlusion arising from pruning treatments. Wounds resulting from the artificial pruning of smaller branches occlude significantly faster than those of larger ones. This correlation has been confirmed by various studies on a broad range of tree species including valuable broadleaved species such as red oak (*Q. rubra* L.), ash or sycamore (Petruncio et al. 1997, Joyce et al. 1998, Hein and Spiecker 2007, Seifert et al. 2010, Nicolescu et al. 2013, Dănescu et al. 2015). The diameter of pruned branches is essential when considering wound occlusion time. Recommendations that branches of wild cherry should be pruned before they reach a maximum threshold of 2.5 cm to 3.0 cm can be reinforced (Pryor 1988, Spiecker and Spiecker 1988).

The results of our study confirm a significant reduction of occlusion time for increasing *irO*. Moreover, it could be proven that *irO* outweighs the influence of *BD* as far as occlusion time is concerned. This corresponds with the findings of Finnis (1953) relating to *P. menziesii*. The correlation between *irO* and *OT* suggest that thresholds for ideal pruning diameters cannot be generalised but must be site related and that artificial pruning should be focused on the most vital individuals within a stand. Similar conclusions have been drawn by Žumer (1966) and Dănescu et al. (2015). The sampled wild cherry within this study were derived from a site displaying an average annual ring width increment of approximately 3 mm during the time of occlusion. Since growth rates of 4 to 5 mm have also been measured for trees on this site, the application of silvicultural treatments to promote fast growth can also be suggested. This may include a reduction of competitive pressure amongst trees with lower annual radial increment applied after pruning treatments in order to support rapid wound closure.

The results of this study show a correlation between pruning wound occlusion time and the occurrence of decay. With increasing occlusion time the frequency and severity of decay also increases. This concurs with results presented by both Pretzsch et al. (2010) and Seifert et al. (2010). We suggest that if a pruning wound is occluded within two years, there is limited risk of decay. This study showed that coupled with an occlusion time of four years the first instances of stem decay are observed. Any further prolongation of occlusion time increases the frequency and intensity of infections and consequent decay. As a result, it is of vital importance for silvicultural management to aim for full occlusion within a maximum of three years. Location and site quality are important parameters for radial increment increases, and therefore also play a major role in the occlusion process of pruning wounds. Seifert et al. (2010) developed a model whereby dependent on annual radial increases, branch diameter thresholds to avoid decay arising from pruning wounds can be suggested. They also found that wild cherry located on poor sites invested greater energy in the defence of fungal infection of pruning wounds, and thus presenting a lower decay rate for the same occlusion time as trees located on higher quality sites. The sampled wild cherry within this study were derived from only one site, displaying an average ring width increment of approximately 3 mm during the time of occlusion. According to the model by Seifert et al. (2010), on a site comparable to the one we investigated, branches in the diameter range of up to 2.5 cm can be pruned without or with modest risk of severe stem decay. This is in agreement with results presented within this study.

All three variables manipulating wound occlusion can be influenced by forest managers: *BD* can be minimised by pruning both early and repeatedly in the rotation, *BSL* can also be minimised by improved pruning technique and accuracy, this can be reinforced by training forest workers in best practice techniques. Finally, *irO* can be maximised by utilising targeted silvicultural measures that encourage diameter growth coupled with applied pruning treatments. The selective pruning methodology where large diameter and steeply angled branches are removed within the entire length of the planned branch free bole vs. a classical whorl-wise pruning methodology allows the forest manager to effectively control factors such as *BD* while retaining a high radial increment for a decreased wound occlusion time resulting in a reduced risk of decay.

Conclusion

We conclude that if valuable timber is to be produced the artificial pruning of wild cherry must aim for an accurate pruning cut, leaving the remaining stubs short. We suggest that branches to be pruned should not exceed a diameter of 2.5 cm on order to promote a rapid wound occlusion which can limit the potential for decay. Finally, it can be concluded that the promotion of large radial increments during wound occlusion is of major importance to ensure swift occlusion of the pruning wound.

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Annals of Silvicultural Research
40 (2), 2016: 134-147

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Research papers

Use of innovative groundcovers in Mediterranean afforestations: aerial and belowground effects in hybrid walnut

Angelo Vitone[1*], Jaime Coello[2], Miriam Piqué[2], Pere Rovira[2]

Received 18/04/2016 - Accepted 27/10/2016 - Published online 28/11/2016

Abstract - Forest restoration in the Mediterranean area is particularly limited by water scarcity in summer and by weed competition, especially within the first years after establishment. The negative impact of these factors can be mitigated through environmentally friendly and cost-effective techniques which favour root development. This study describes the results of innovative weeding techniques in a reforestation carried out in a former agricultural field in Solsona, NE Spain, under Continental Mediterranean Sub-humid climate conditions. The tested weeding techniques included both novel groundcovers (based on prototypes built on a new biodegradable biopolymer, jute treated with resin and recycled rubber) and reference techniques, i.e. herbicide application, polyethylene and commercial biofilm groundcovers. We studied the response of hybrid walnut (*Juglans x intermedia*) to the application of these techniques during the first vegetative period in terms of survival, aerial growth and aboveground and belowground biomass allocation. The innovative groundcovers produced generally similar outcomes as the reference techniques with regard to tree survival and growth and resulted better in the case of belowground and, to a lesser extent, total tree biomass. Although preliminary, our results suggest that the tested novel groundcovers, notably the model based on treated jute, may represent a promising alternative to plastic mulching and herbicide application in afforestation of agricultural lands under Mediterranean-continental conditions. Besides these promising productive results, the novel groundcovers bring together relevant technical and environmental benefits, related to their use (not requiring removal or being reusable) and composition, based on biodegradable or recycled materials.

Keywords - Biomass allocation, Eco-innovation, Forest restoration, *Juglans,* Mulching, Reforestation

Introduction

Mediterranean climate is characterized by summer drought and high air temperatures (IPCC 2007, Senatore et al. 2011). The annual potential evapotranspiration (PET) often doubles the rainfall, causing significant water stress to plants (Flexas et al. 2006). It is expected that this condition becomes worse in the future because of climate change, as a result of the projected temperature rise and the more intense drought periods (Giorgi and Lionello 2007). Indeed, the Mediterranean region has faced wide climate shifts in the past (Luterbacher et al. 2006), and it has been identified as one of the most prominent 'hotspots' in future climate change scenarios (Giorgi 2006, Ulbrich et al. 2006).

The most critical factors limiting the successful establishment of a new plantation in the Mediterranean context are the high incoming radiation, the air temperature and the low summer rainfall (Verdú and Garcìa Fayos 1996). The heavy radiation may lead to photo-damage (Methy 1996) and cause significant soil water losses due to evaporation (Rey Benayas 1998). This factor, together with low summer rainfall, results in severe water stress particularly critical for young plants with an underdeveloped root system (Coll et al. 2003). Another major factor leading to an enhanced water stress in young trees is the weed vegetation (Rey Benayas et al. 2003). In the Mediterranean area, weeds affect negatively young trees especially with regard to water (Picon-Cochard et al. 2001) and, then, to soil nutrients (Nambiar and Sands 1993) and light availability.

Together with an adequate soil preparation (deep soil ripping, micro-catchments), and the use of adapted seedlings (in terms of species, provenance and root/shoot ratio), there are many techniques that can be applied to facilitate young trees in the first years since the plantation (i.e the installation phase). These can reduce summer water shortage, exacerbated by weed competition, even though their effectiveness and feasibility depend upon the characteristics of the sites of concern. In the case of competing vegetation, the most common techniques applied in temperate areas are the mechanical and chemical weeding (Willoughby et al. 2009). Mechanical weeding has the disadvantage of requiring a not negligible use of resources and may damage plants

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http://dx.doi.org/10.12899/asr-1195

(George and Brennan 2002). Chemical weeding is an adequate cost-effectiveness solution in many circumstances (Thiffault and Roy 2011). This technique requires however recurrent application and raises significant social/environmental opposition (Bond and Grundy 2001). Its utilization in forest ecosystems is thus increasingly regulated or even banned (Willoughby et al. 2009). Mulching soil with groundcovers is being increasingly considered as a suitable technique alternative to recurrent weeding, especially in the framework of minimizing the number of interventions (Scott Green et al. 2003). Mulching has proven to reduce the vegetative competition in the root zone (Adams 1997) and to mitigate soil water evaporation (McDonald et al. 1994), thus increasing soil water availability. Mulching also increases the availability of nutrients for trees (Wilson and Jefferies 1996). Some mulching models (e.g., films) raise the soil temperature favouring the nutrient cycle and therefore root growth (Ghosh et al. 2006, Kasirajan and Ngouajio 2012).

The application of mulching often results in growth gain in juvenile phase, especially under condition of high vegetative competition (Scott Green et al. 2003). The most common products for film mulching are polyethylene and polypropylene. The main advantage of these materials concerns affordability, easiness of application, long-lasting duration and effectiveness against weeds (Arentoft et al. 2013). Their main drawback is that these products derive from unsustainable raw material (petroleum) and their removal is very expensive (McCraw and Motes 1991). In the last years, bio-based film mulches (i.e. biodegradable and obtained from renewable sources) are becoming available in the market. This allows keeping the advantages of plastic mulches while avoiding the need for removal (Kasirajan & Ngouajio 2012). The main factor limiting the use of biofilm mulches in comparison with plastic-based ones is their higher cost. While a 100 x 100 cm polyethylene sheet can cost 0.4-0.5 €, a similar piece of biofilm may be as expensive as 2-2.5 €.

Goal of the study is to evaluate the effectiveness of new groundcover types in controlling weeds and stimulating seedling growth, both above-ground and below-ground, within the first years in a hybrid walnut plantation in a Mediterranean-continental area. These techniques were developed with the aim of improving forest restoration projects in Mediterranean and temperate conditions from an environmental, technical and economic viewpoint. Our hypothesis is that the new groundcovers should increase tree growth compared to the unweeded trees, similarly to the reference weeding techniques (i.e. plastic mulching and herbicide application).

Materials and methods

Study area and plantation description

The study was carried out in Solsona, Lleida, NE Spain, at coordinates 42°00'09.71"N 1°31'46.09"E, elevation of 672 m a.s.l.. The climate is Mediterranean-continental sub-humid (Martín-Vide 1992), with an average annual temperature of 12.0°C (average temperature at the warmest and coldest month is 21.4°C and 3.7°C, respectively). Mean annual precipitation is 683 mm, 165 mm during summer period (Ninyerola et al. 2005). The plantation was established in spring 2014 in a flat field, previously used for cereal production (wheat and barley).

Soil texture is loamy-clay (32% clay, 40% silt and 28% sand). During the plantation the soil was prepared by crossed sub-soiling with ripper (45 cm depth). Plants were installed manually, in pits sized 40 x 40 x 40 cm. The plantation scheme was regular, 3 x 3 m. The vegetative material was hybrid walnut (*Juglans* x *intermedia*) MJ-209xRa, bare rooted, 40/60 cm high. Aim of the plantation was the production of valuable timber for veneer industry.

Experimental design and treatments

The seven experimental treatments, described in Table.1, include three innovative groundcovers, three reference techniques against competing vegetation and a control (unweeded trees). These treatments were compared following a randomized block design with 6 blocks, each of them containing 10 trees per treatment (60 trees per treatment, 420 experimental trees).

Table 1 - Description of the 7 experimental treatments. Each individual treatment refers to 80x80 cm area.

Treatment type	Description	Treatment code
Control	*No weeding treatment	Unweeded
Reference weeding techniques	* Herbicide application (glyphosate, 14.4 cm3 tree-1 at 1.25%) applied in May via backpack sprayer	Comm_HER
	*Commercial black polyethylene film, anti-UV treated, 80 µ thick	Comm_PE
	* Commercial green biodegradable woven biofilm	Comm_BF
Innovative groundcovers	* Recycled rubber based mulch, anti-UV treated, long-lasting and not requiring fixation (1.5 mm thick)	New_RUB
	* Woven jute cloth treated with bio-based resin for increased lifetime, 100% biodegradable	New_JUTE
	* Black new biopolymer-based frame 100% biodegradable, fused to a black commercially available biodegradable film	New_BF

Data collection and measurements

Survival and vegetative status

Tree mortality and vegetative status were assessed visually in October 2014. A tree was considered to reveal vegetative problems when the apical shoot was dead or when showing basal sprouting.

Stem growth

Basal diameter (measured with digital caliper 5 cm over the ground level on a painted mark) and total height (by measuring tape) were collected both at planting (April) and at the end of the vegetative period (October). Annual diameter and height increment were calculated as the difference between first and second measurement.

Biomass allocation study

Two living trees per treatment and block (84 in total) were randomly chosen in November 2014. These trees were pulled out carefully by a small bobcat-type backhoe excavator, keeping a full rootball with all fine roots intact. Uprooted trees were immediately placed in labelled paper bags and stored at 4ºC until being processed at the lab within the subsequent 7 days. Following Schall et al. (2012) and Nanayakkara et al. (2013), the roots were put in a bucket with water to soften them and dilute soil and then rinsed gently with tap water, without damaging the roots and recovering all broken roots from each tree. Then, the trees were divided into three components: stem, coarse roots and fine roots (thickness >2 and <2mm, respectively), by using scissors for cutting and digital caliper for measuring thickness. Each component was located into a labelled aluminium tray, where they were oven-dried at 70°C for 72 hours. Finally, dry components were weighed. The variables resulting from this process are the absolute (g) and relative (% with respect to the total of the tree) biomass for each component.

Weather in 2014

The study took place within the 2014 growing season, characterized by an anomalous high rainfall amount in the July-September months (313 mm), value that almost doubled the average historical reference value of 165 mm. There was no relevant dry period during the year according to the Bagnouls & Gaussen diagram from January to October 2014 (Fig. 1).

Data analysis

Data analysis consisted of evaluating the effect of the different weeding techniques. The survival and vegetative status were analyzed by means of the Pearson's Chi-square (χ^2) test. Tree growth and biomass allocation were analyzed through a one-way analysis of variance (ANOVA; p-level < 0.05). When significant differences between treatments resulted from ANOVA, these were evaluated by means of post-hoc Tukey's HSD test. The analysis was performed with the software Statistica 7.1, 2005 (StatSoft Inc. USA).

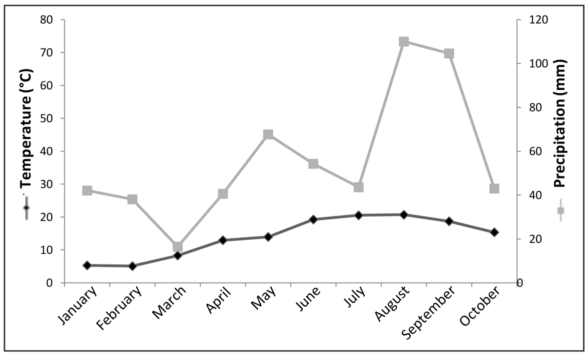


Figure 1 - Bagnouls & Gaussen diagram for the vegetative period 2014 in the study area.

Results

Survival and vegetative status

During the first vegetative period overall mortality rate was very low (five trees or 1.2%) with the higher mortality rate in the unweeded trees (four trees out of five). As for the vegetative status, 16.7% of trees showed some kind of vegetative problem (Fig. 2). The Pearson's χ^2 test did not explain any relationship between treatment and incidence of mortality or vegetative problems.

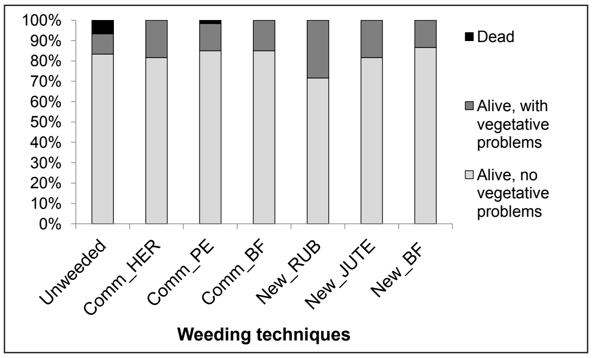


Figure 2 - Percentage of trees under each category of survival and vegetative status.

Aerial tree growth: diameter and height

Aerial growth (both in diameter and height) was affected by the different weeding treatments applied. Diameter growth was significantly improved by all the weeding treatments compared to the Unweeded-control, with diameter values which were doubled or tripled. However, no significant difference was found between the 6 weeding techniques tested (Fig. 3).

Height growth showed the same trend, with Unweeded-control providing the lowest values, although only New_JUTE and New_BF provided significantly higher results (Fig. 4).

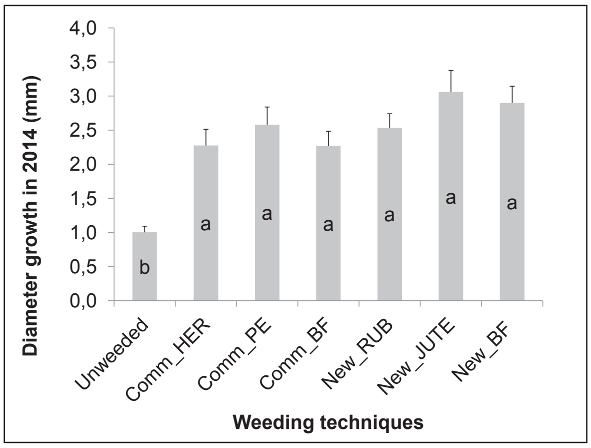


Figure 3 - Mean walnut diameter growth in 2014, subject to different weeding techniques; whiskers indicate standard error of the mean. Different letters indicate significant differences at the p<0.05 level, grouping according to Tukey's HSD post hoc test.

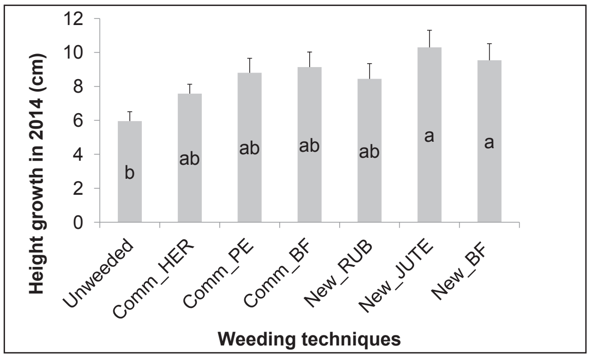
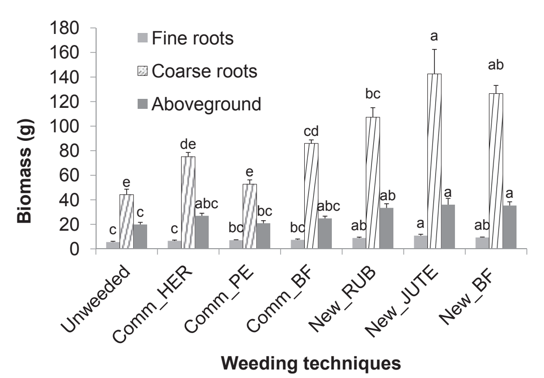


Figure 4 - Mean walnut height growth in 2014, subject to different weeding techniques; whiskers indicate standard error of the mean. Different letters indicate significant differences at the p<0.05 level, grouping according to Tukey's HSD post hoc test.

Biomass allocation

The weeding treatments affected the allocation of biomass among the different tree components, both for absolute (total biomass per component) and relative (percentage of biomass for each component with respect to total tree biomass and root/shoot ratio) variables considered. All innovative weeding techniques (New_RUB, New_JUTE, New_BF) led to significantly higher biomass than Unweeded-control for all tree components, while Comm_BF improved biomass production in coarse roots, total roots and total biomass in comparison to Unweeded-control (Figure 5). The comparison between the different weeding treatments highlights a consistent trend: New_JUTE and New_BF resulted in higher biomass allocation than all three reference techniques for most compartments, while New_RUB only improved biomass production with respect to Comm_PE and Comm_HER at most cases.

In the case of the relative distribution of biomass among the various compartments, Unweeded and Comm_PE provided a lower share of biomass in coarse roots than most of other treatments, and a higher proportion of fine roots and aboveground biomass (Fig.6).



Belowground	49.8 **(e)**	81.6 **(de)**	59.8 **(e)**	93.3 **(cd)**	116.1 **(bc)**	153.4 **(a)**	135.8 **(ab)**
Total biomass	69.8 **(d)**	108.7 **(bcd)**	80.7 **(cd)**	118.2 **(bc)**	149.5 **(ab)**	189.4 **(a)**	171.2 **(a)**

Figure 5 - Mean biomass allocated to each tree compartment (g) as a response to the different treatments. Whiskers indicate standard error of the mean. Different letters indicate significant differences at the p<0.05 level, grouped according to Tukey's HSD test. Below the graph are given the mean total root biomass (belowground) and total seedling biomass, with the letters in brackets showing the grouping according to Tukey's HSD test.

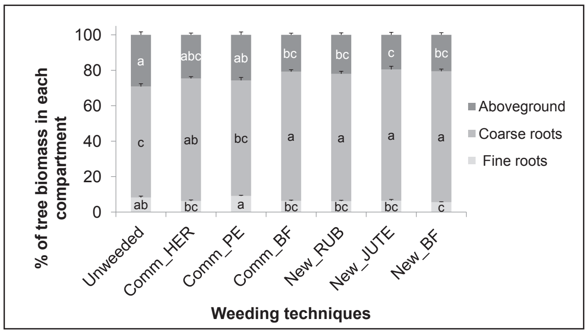


Figure 6 - Mean relative allocation of biomass in each compartment, with respect to total tree biomass (%); whiskers indicate standard error of the mean. Different letters indicate significant differences (p<0.05), grouped by Tukey's HSD test.

Weeding techniques had a significant effect on root/shoot ratio. Also for this parameter New_JUTE showed significant higher values than Comm_PE, while both New_JUTE, New_BF and Comm_BF provided significant higher values than Unweeded (Fig.7).

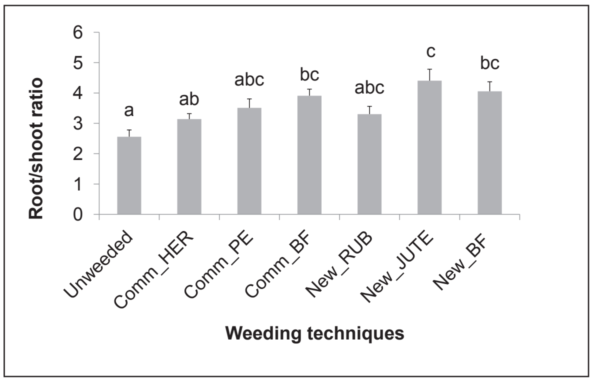


Figure 7 - Mean root/shoot ratio for the different weeding treatments; whiskers indicate mean standard error. Different letters indicate significant differences (p<0.05), grouped by Tukey's HSD test.

Discussion

The analysis highlighted the effect of different weeding techniques on survival, vegetative status, aerial growth and biomass allocation of hybrid walnut seedlings, during the first growing season. We found a positive effect of all weeding treatments in most variables, compared to the unweeded trees.

Seedling survival and vegetative status

The survival of seedlings after one growing season is high (98.8%). Among the five dead plants of the study, four corresponded to the Unweeded treatment, suggesting the negative effect of competition (Chaar et al. 2008). The vegetative status was generally good, 82.1% of seedlings being healthy. No linkage was checked between the different treatments applied and the occurrence of vegetative problems.

Tree aerial growth

Weeding techniques had a remarkable positive effect compared to unweeded trees (Haywood 2000, Athy et al. 2006). Diameter growth of all weeding treatments resulted to be superior to unweeded trees as already observed in other research trials (Bendfeldt et al. 2001, Paris et al. 2005). Tree height growth, in New_JUTE and New_BF showed higher values than unweeded trees, as observed by previous studies on walnut (Haywood 1999, Smith et al. 2000). Significant tree growth differences between weeded and unweeded trees but not significant differences among different weeding techniques was also found in other analyses (Abouziena et al. 2008, Maggard et al. 2012).

Absolute biomass allocation

The analysis of biomass allocation among the different tree compartments (fine roots, coarse roots, aerial biomass) showed a clear effect of the different treatments applied. All innovative mulching techniques, and Comm_BF in most cases, increased the biomass of all tree compartments compared to unweeded trees, as found in previous studies assessing mulching techniques (Scott Green et al. 2003). By excluding weed competition, mulching increases water, nutrients and light available for the trees (Wilson and Jefferies 1996, Liu et al. 2003), and in turn facilitates an increase in biomass productivity (Haywood 1999). The case of root biomass is especially relevant in the study of young tree plantations, since it allows the exploration of larger soil volume and increases its resistance to prolonged water stresses in the subsequent years (Vallejo et al. 2012). The innovative mulches improved seedling rooting during the installation phase compared to Unweeded and reference weeding techniques.

Only one mulching technique (Comm_PE) did not increase significantly tree biomass of any compartment compared to unweeded trees. The reason could be related to the particular features of polyethylene mulch, i.e. a continuous plastic layer fixed to the ground, thus limiting water and air circulation and considerably reducing the soil water evaporation (Sharma et al. 1998). In general, this feature is an advantage when water availability is the main limitation (McCraw and Motes 1991) linked to drought and/or poor soil water retention. However, in the case of concern, the trial took place on a heavy textured soil and under a very wet year, and the same feature may have resulted in excessive water accumulation in the soil, which is in turn an undesirable condition for walnut (Becquey 1997). Indeed, the best results were obtained by New_JUTE mulch, a woven-structure mat with rather high permeability to water, allowing infiltration during a rainfall event and evaporation afterwards thus enhancing tree growth (Debnath 2014). The effectiveness of jute mulching has also been demonstrated in other studies, especially in agriculture (Tomar et al. 2005) not only for its weed control potentialities, but also for its mechanical and hydraulic characteristics, even concerning the regulation of soil temperature (Sanjoy 2014).

Comm_BF, leading to slightly better results than the other reference techniques, is also a woven mat with a similar structure as New_JUTE (55 threads cm^{-2} in front of 58 threads cm^{-2}, respectively) but with a notably different density (110 g m^{-2} in front of 460 g m^{-2}) and hygroscopic properties: while Comm_BF does not absorb water, New_JUTE consists of vegetal fibres which need to be moistened before becoming permeable. As a result, Comm_BF may allow a slight rainfall to penetrate in the soil but its capacity to prevent its evaporation will not stand for long time. On the other hand, New_JUTE is expected to require a heavier rainfall to allow water to reach the soil, but it would be therefore retained for longer time. In our study, with a rather high supply of water, New_JUTE performed better than Comm_BF in terms of belowground biomass, probably linked to a more efficient prevention of soil water evaporation during the warmest periods of summer, while it still allows sufficient soil aeration, opposed to Comm_PE.

Regarding New_BF and New_RUB, they are both black film mulches, although contrary to Comm_PE their surface is not continuous but consists on assembled pieces which leave some air exchange through the film, although closed enough as to impede weed growth through the mulch.

Finally, Comm_HER did not improve the results of unweeded trees regarding biomass production of any tree component. In contrast, the use of the same herbicide with the same concentration and time of application yielded during four years (2011-2014) created much more favourable results than the use of four different mulching models in a trial located two kilometers away from the field of this study, with similar soil features and the same tree species (Coello et al. *submitted*). In the mentioned study, the area per tree treated with herbicide was 100 x 100 cm, while in our study the treated area was similar to mulch size (80 x 80 cm), thus one third smaller. Moreover, in our study the wet conditions in 2014 might have boosted weed proliferation and its competitiveness during summer, reducing the efficiency of a one-time, spring herbicide application.

Relative biomass allocation

The survival of seedlings during summer is closely related to the development of the root system, rather than to the aerial organs (Lloret et al. 1999, Villar-Salvador et al. 2012). A more developed root system can more easily absorb deep (Canadell and Zedler 1995, Pemán et al. 2006) and surface water (Hilbert and Canadell 1995), and allows a more efficient extraction of nutrients (Wein et al. 1993, Lambert et al. 1994). The root/shoot ratio is a trait describing how the tree distributes the available resources (Lamhamedi et al. 1998), it being very important under water-limited condition, like Mediterranean climates (Lloret et al. 1999). It is generally accepted that a high root/shoot ratio indicates a better chance of survival under Mediterranean conditions (Navarro et al. 2006, Jacobs et al. 2009). Plants with a high root/shoot ratio are considered as better performers in water-limited sites (Royo et al. 1997), as they consume less water than plants with opposite traits (Leiva and Fernàndez-Ales 1998). In our study, the root/shoot ratio was found to be especially high for the treatments resulting in highest biomass production of compartments altogether (New_JUTE and, to a lesser extent, New_BF and Comm_BF).

Fine roots and coarse roots are the components of belowground biomass, their dry weight being proportional to the volume of soil that they can explore (Tufekcioglu et al. 1999). Fine roots represent a dynamic portion of belowground biomass, i.e. the main component dedicated to nutrients uptake, and representing a significant part of net primary production (Buyanovsky et al. 1987). On the other hand, coarse roots production is closely linked to resource availability (Albaugh et al. 1998) and especially involved in carbohydrate and nutrient storage (Comas et al. 2013) making the tree more resistant to stresses. In our study, mulching technology, particularly the new versions, enhanced a higher production of root biomass, especially among the coarse component, thus being an indicator of successful plantation.

Conclusions

Our preliminary study demonstrated the importance of weeding for increasing both aerial and belowground early tree growth in productive Mediterranean-continental conditions.

Mulching was especially effective on reducing competition by herbaceous species for water and nutrients. Among the mulching techniques tested, a novel model based on woven jute proved to be particularly successful, with enhanced results for all the traits studied, probably associated with its adequate permeability rate, which was beneficial in a wet year as 2014. Other innovative film mulches based on new biopolymers and on recycled rubber, and to a lesser extent a commercial biofilm, also led to superior results in comparison to unweeded trees, and to trees subjected to herbicide application or to polyethylene mulching.

The evaluated novel mulches demonstrated their technical adequacy, in addition to the environmental advantages compared to reference techniques; both the new biopolymer formulation and the treated jute films are 100% biodegradable, this avoiding the need for their removal and being a notable advantage compared to plastic groundcovers. The new mulch based on recycled rubber is not biodegradable, but it is made of recycled waste and its long durability (estimated in up to 15 years in outdoor conditions) makes it especially suitable for long-term applications where removal costs should be minimized: urban forestry, afforestation of easily accessible land, etc.

These results correspond to a preliminary phase of study, and must be confirmed with data from further years and further study areas in order to adequately assess the potential of these techniques for forest restoration under Mediterranean conditions with regard to their effect on tree survival and growth.

Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme managed by REA-Research Executive Agency http:// ec.europa.eu/research/rea (FP7/2007-2013) under grant agreement n° 606554 - SUSTAFFOR project ‘Bridging effectiveness and sustainability in afforestation / reforestation in a climate change context: new technologies for improving soil features and plant performance’. We are grateful to Sergio Martínez for his support during field and lab work and to Alejandro Borque, Sílvia Busquet, Ina Krahl, Guillem Martí and Aida Sala for their essential support during the establishment of the field trial.

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Technical notes

Tree-oriented silviculture for valuable timber production in mixed Turkey oak (*Quercus cerris* L.) coppices in Italy

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Received 21/09/2016 - Accepted 27/10/2016 - Published online 28/11/2016

Abstract - Coppice management in Italy has traditionally focused on a single or few dominating tree species. Tree-oriented silviculture can represent an alternative management system to get high value timber production in mixed coppice forests. This study illustrates an application of the tree-oriented silvicultural approach in Turkey oak (*Quercus cerris* L.) coppice forests. The rationale behind the proposed silvicultural approach is to combine traditional coppicing and localized, single-tree practices to favor sporadic trees with valuable timber production. At this purpose, a limited number of target trees are selected and favored by localized thinning. In this study, the effectiveness of the proposed tree-oriented approach was compared with the customary coppice management by a financial evaluation. Results showed that the tree-oriented approach is a reliable silvicultural alternative for supporting valuable timber production in mixed oak coppice forests.

Keywords - single-tree selection, localized thinning, valuable tree, mixed forests, sporadic tree species

Introduction

Coppice is a widespread silvicultural system in Mediterranean European countries where it covers about 23 million hectares (FOREST EUROPE, UNECE and FAO 2011). In Italy, coppice is the most frequently adopted silvicultural system in private forests, and it amounts to about 56% of the total forest area (http://www.inventarioforestale.org). The success of coppice system can be explained considering the advantages to forest owners, like simple management, easy and rapid natural regeneration, faster initial growth rate than the high forest system (Ciancio et al. 2006). Deciduous Turkey oak (*Quercus cerris* L.) occupies the intermediate vegetation belt between sclerophyllous and mountain broadleaved forest over one million hectares (Barbati et al. 2014). Turkey oak represents an economically relevant species with regards to coppice management. On the whole, tree species composition in the dominated Turkey oak forests usually reflects the natural vegetation, even though the diffusion of a few species (e.g. maples, ashes, service trees, wild service trees, hornbeams) has been frequently reduced by management in the past.

With the exception of chestnut woods, coppice management has been traditionally focused on the production of fuelwood and charcoal, which in the past have represented fundamental resources for people living in rural areas (Chianucci et al. 2016b). This approach has traditionally favored the wood production by dominant tree species, at the expenses of often neglected sporadic ones (Chianucci et al. 2016a). More recent changes in the management perspective aimed at integrating economic, social and environmental aspects have led to consider more sustainable silvicultural approaches for coppice woods (Corona 2014). In this line, sporadic tree species may have a potentially interesting role from the ecological and productive point of view (Spiecker 2006, Mori et al. 2007, Mori and Pelleri 2014, Manetti et al. 2016).

Sporadic tree species are less competitive than dominant tree species, and thus their conservation and valorization require specific, tree-oriented silvicultural approaches (Mori et al. 2007). The tree-oriented silvicultural concept has been developed in Central Europe for managing oaks, beech and spruce high forests (e.g. Abetz 1993, Sevrin 1994, Bastien and Wilhelm 2000, Abetz and Kladtke 2002, Wilhelm 2003, Oosterbaan et al. 2008, Spiecker et al. 2009) and specifically for protecting and valorizing of sporadic tree species (e.g. Spiecker 2003, Sansone et al. 2012, Pelleri et al. 2013, Mori and Pelleri 2014).

The objective of tree-oriented silviculture is obtaining high-quality timber assortments in a relatively short rotation period (Oosterbaan et al. 2008) simultaneously minimizing the operational costs. A

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http://dx.doi.org/10.12899/asr-1198

limited number of target trees are selected, and their growth is supported by reducing surrounding competitors by frequent, repeated thinning from above (Kerr 1996, Perin and Claessens 2009, Lemaire 2010). Such interventions allow high crown enlargement, and therefore high and uniform diameter growth of released trees. Recent studies have demonstrated that this approach can be successfully applied to coppice woods (Mori and Pelleri 2014; Manetti et al. 2016).

In this technical note we illustrated the application of the tree-oriented silviculture approach in mixed (deciduous) Turkey oak coppice stands. Specific aims are:

i) to provide an overview of the proposed tree-oriented silviculture approach;
ii) to evaluate the financial feasibility of the investments required for the implementation of proposed approach at the forest district level;
iii) to illustrate a case-study of practical implementation of the silvicultural approach.

Description of the adopted silvicultural scheme

The silvicultural scheme here proposed is based on a two-fold system of intervention, designed to integrate the tree-oriented concept with customary coppicing. In Central Italy, customary coppice rotation for Turkey oak stands is 20 years, which approximately corresponds to the culmination of mean annual volume increment under average site conditions (Bianchi and La Marca 1984). Customary coppicing practices are combined with other interventions specifically focused on fostering tree growth of a few selected sporadic tree species (hereafter target trees). These tree-oriented interventions differ according to the development of target trees, as indicated by Sansone et al. (2012) and Mori and Pelleri (2014). Basically, there are three different stages of growth, here indicated as T1, T2 and T3 (Fig. 1), which may occur at different times within the rotation.

(T1) The first tree-oriented interventions occur at mid coppice rotation (at 10, 30, 50, 70, 90, 110 years, …). In this stage the young target trees are selected, and their growth is favored by localized thinning from above of the main competitors to support uniform crown enlargement (Table 1). Pruning of target trees may also be carried out in this stage to accelerate the qualification of a branch-free bole and reach more than 2.5 meters length.

(T2) The second stage of growth of target trees occurs at the end of coppice rotation (at 20, 40, 60, 80, 100, 120 years, …). During this stage, a protective ring is being created around the target trees to favor individual crown enlargement with localized thinning every 6-10 years (Fig. 1). The minimum diameter of protective ring corresponds to the mean height of coppice standards. If the target trees are close to each other, a single protective ring is created around them. Pruning of target trees may also be carried out in this phase to complete the qualification of the branch-free bole.

(T3) The third stage of growth occurs when the target trees reached a size adequate to compete with the dominant trees. During this stage, the protective ring is removed and the target trees are left to grow further until they reach the awaited harvesting size. The felling of the target tree coincides with the coppicing period (at the ages of 40, 60, 80, 100, 120 years).

The proposed approach is similar to the one proposed t by Mori et al. (2007) and Mori and Pelleri

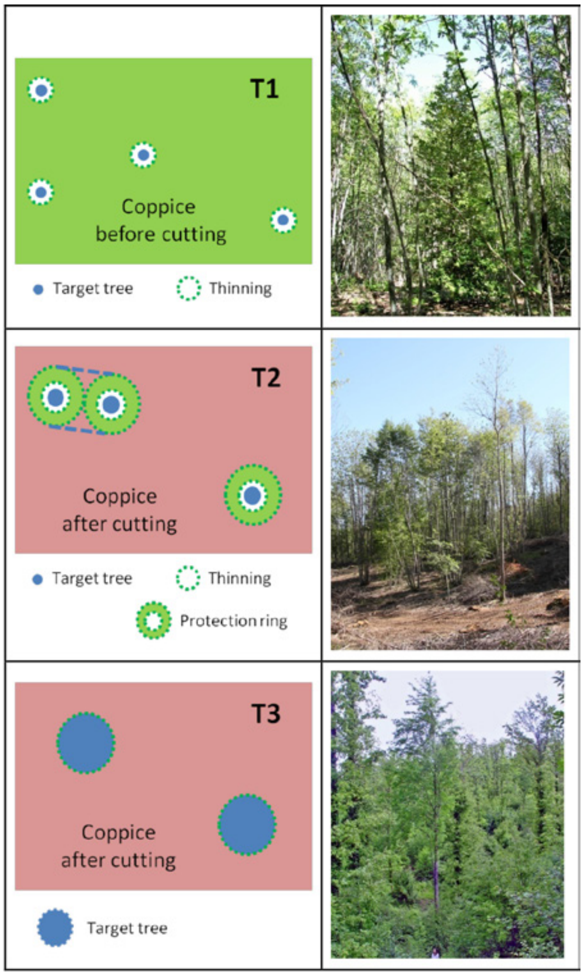

Figure 1 – Growth stage T1: localized thinning undertaken to promote target valuable sporadic tree species in a young coppice. Growth stage T2: coppice stand cut at the rotation end where a number of trees is being left as a protective ring around the target trees. Growth stage T3: coppice stand cut at the rotation end where protective trees are being removed to allow free growth of target trees.

(2014) for Turkey oak coppices, but differs as for the transition period herein of 80 years (previous studies indicated 72 years). In the following stage, the number of target individuals (selected, thinned and felled) of sporadic tree species is expected to remain constant over time and homogenously distributed in the three stages of growth. A synthetic description of the model is reported in Table 1 considering an observation time of 120 years. The main features of the proposed scheme are:

- about 6 target trees per hectare selected at the each mid coppice rotation for timber production (at 10, 30, 50, 70, 90, 110 years);
- coppicing every 20 years (coppice rotation);
- harvesting of about 6 mature target trees per hectare at the end of the transition period (80 years and every 20 years after 80 years);

The above features need to be considered as general guidelines, and they need to be calibrated and adapted to the actual site and stand bio-ecological conditions.

1. Financial assessment

Methodological considerations

The feasibility of the investments required for the implementation of the proposed silvicultural scheme was carried out according to the financial evaluation methods proposed by Andrighetto and Pettenella (2013) and Marone et al. (2014). The financial evaluation is aimed at verifying the profitability of the approach compared with customary coppicing, with regards to the following indicators:

- Net present value (NPV);
- Internal rate of return (IRR), i.e. the discount rate corresponding to a zero NPV;
- Payback period;
- Cash flows;
- Revenues to costs ratio (R/C).

The analysis has considered an evaluation period of 120 years. This was motivated because the profitability of the single-tree approach needs to be evaluated after the end of the transition period, when the single-tree approach is meant to provide a constant production through time (6 target trees every 20 years after 80 years).

Thinning cost was estimated based on real data collected in demonstrative areas of the LIFE project PProSpoT (Marone and Fratini 2013, see also http://www.pprospot.it). Thinning cost of sporadic tree species was included within coppicing costs. To avoid the influence of fluctuations in market prices

Table 1 - The proposed silvicultural (tree-oriented) scheme for Turkey oak coppice stands in Central Italy.

Phase		T1	T2	T1	T2-T3	T1	T2-T3	T1	T2-T3	T1	T2-T3	T1	T2-T3
		Transition period								*Ordinary regime*			
		Years											
Operations	0	10	20	30	40	50	60	70	80	90	100	110	120
Selection and marking of the target trees T1 for timber production (n/ha^{-1})		6		6		6		6		6		6	
Selection target trees T1 for biodiversity (n/ha^{-1})		2											
Marking main competitors (n/ha^{-1})		8	8	14	6	12	6	12	6	12	6	12	6
Pruning target trees T1 (n)		6		6		6		6		6		6	
Localized thinning/girdling of the competitors of target trees T1 (n/ha^{-1}))		8		6		6		6		6		6	
Individuation of protection rings (n/ha^{-1})			8		6		6		6		6		6
Pruning target trees T2 (n)			6		6		6		6		6		6
Localized thinning inside protection rings T2 (n/ha^{-1})			8	8	6	6	6	6	6	6	6	6	6
Logging woods resulting from thinning (n)			8	14	6	12	6	12	6	12	6	12	6
Release of target trees T3 (n/ha^{-1})					8		8		8		8		8
Felling and logging of mature target trees (n)									6		6		6
Coppice harvesting (ha)	The whole surface		Net surface without the protection rings		Net surface without the protection rings		Net surface without the protection rings		Net surface without the protection rings		Net surface without the protection rings		Net surface without the protection rings
Total number of target trees (n/ha^{-1})	0	8	8	14	14	20	20	26	20	26	20	26	20

Table 2 - Market prices (€ m^{-3}) of roundwood from sporadic tree species (from Marone et al. 2014 *modified*).

Tree species	First timber quality class	Second timber quality class	Third timber quality class
Cherry	340	226	113
Service tree	665	443	221
Wild apple	300	200	100
Field maple	300	200	100
Wild pear	665	443	221
Field elm	340	226	113

on stumpage, we considered a null stumpage value by assuming the coppicing costs and the stumpage price as 5,000 € ha^{-1} and 50 € ton^{-1}, respectively, and a coppice yield of 100 tons ha^{-1} at the end of coppice rotation. Indirect costs have been identified in the reduction of coppice yield due to the release of target trees, which was assumed reducing the exploitable coppice area by 180 m^2 per target tree.

Timber market prices considered were selected from comparable local stand and site conditions (Table 2). To perform the calculation of the financial indicators, we adopted a discount rate decreasing over time (3.5% after the first 30 years; 3.0% between 31 and 75 years; 2.5% between 76 and 120 years), consistently with the approach proposed by HM Treasury (2011) for a proper evaluation of public resources in investments lasting several decades.

The revenue of single-tree silviculture heavily depends on the target tree species. Table 3 lists result from a field survey in Viterbo (Central Italy) of the main production and composition from the most diffuse sporadic tree species in a coppice stand representative of mean conditions in Turkey oak coppices in Central Italy; these values were considered in the financial evaluation. The post-intervention increments were verified through appropriate monitoring activities carried out in Tuscany, three years after the interventions in various forest stands within the LIFE project PProSpoT. The wood material obtained by coppice thinning to favor T1 and T2 trees and the wood obtained from pruning was considered negligible and thus not considered in the revenue.

Financial simulations

Financial simulations were carried out by analyzing the influence of the following aspects: coppice productivity under canopy cover of target trees and their protective rings; transition period and target timber size; age of selection of target trees and type of selected individuals.

Coppice productivity under canopy cover of target trees and their protective rings

A target tree must grow isolated for the period required to reach a commercially profitable stem diameter. This may trigger shading phenomena in the surrounding coppice shoots depending by the crown size of the target tree, its crown porosity, and the light requirements of coppice shoots (Chianucci 2016). In financial terms, the occurrence of shading phenomena represents an opportunity cost, consisting in the loss of part of coppice productivity. This production loss depends on the number of target trees per surface unit, and it then stabilizes after the transition period (i.e. after 80 years Table 4). Even in case that no productivity loss occurs due to shading effects, there is still a surface loss due to the coverage of the protective rings. Therefore, a reduction in coppice productivity during the transition period (80 years) was considered as part of the financial evaluation (Table 5). A 50% productivity reduction in

Table 3 - Stem diameter at breast height and volume (m^3 tree^{-1}) foreseen by the application of the proposed tree-oriented silvicultural approach during two transition periods (minimum: 60 years; optimal: 80 years) in average site conditions and for different sporadic tree species (expected assortment = 6 m). For cherry (*Prunus avium* L.) it is assumed a growing cycle of 60 years, considering the relatively high growth rate and to prevent plant diseases often occurring at older ages in this species.

Tree species	Transition period 60 years Diameter (cm)	60 years Volume (m^3)	80 years Diameter (cm)	80 years Volume (m^3)
Prunus avium L.	72	2.2	-	-
Sorbus domestica L.	36	0.4	48	1.0
Malus sylvestris Mill.	36	0.4	48	1.0
Acer campestre L.	42	0.5	56	1.3
Pyrus pyraster Burgsd.	36	0.4	48	1.0
Ulmus minor Mill.	36	0.4	48	1.0

Table 4 - Coppice income loss (expressed in percent) in relation to the reduction of coppice wood production in protective rings due to shading effects by the target trees in Turkey oak coppices in Central Italy.

Transition period (years)	Wood production in the protective rings compared to customary coppicing 0%	25%	50%	75%	100%
20	14	14	14	14	14
40	25	22	18	14	11
60	36	30	23	17	11
80	47	38	29	20	11
100	47	38	29	20	11
120	47	38	29	20	11

Table 5 - Financial indicators of the proposed tree-oriented silvicultural approach as a function of wood productivity reduction in protective rings of the coppice stand due to the shading effect by the target trees.

Wood production in the protective rings compared with customary coppicing	R/C	IRR (%)	NPV (euro ha^{-1})	NPV (euro ha^{-1}) year^{-1})	Year when cash flow becomes positive	Payback period (years)
0%	1.01	2.46	100.16	0.83	80	100
25%	1.01	2.63	145.60	1.21	80	100
50%	1.02	3.00	249.20	2.08	80	100
75%	1.02	3.02	259.57	2.16	80	100
100%	1.03	3.35	354.08	2.95	80	80

the protective rings around the target trees is used for all the financial assessments below reported.

Transition period and target timber size

Based on previous studies (Table 3), we considered 60 years as a minimum transition period to reach profitable timber from sporadic species in the proposed silvicultural scheme, while the optimum transition period was foreseen after 80 years, because it offers higher financial performances, leading to permanent property improvement and an increase in income capability. A sixty year transition period may be recommended on fertile sites and in situations where target trees are characterized by relatively fast growth species (e.g. *Prunus avium* L.) (Table 6).

Target trees selection period and type of selected individuals

Financial convenience is compared with respect to 80 year transition period with target trees selected at different times (Table 1). Three situations were compared:

- Early selection: target trees consist of coppice shoots selected at mid coppice rotation (T1);
- Medium-late selection: target trees consist of coppice shoots selected at the end of each coppice rotation (T2):
- Late selection: target trees consist of coppice shoots and standards selected at the end of coppice rotation (i.e. a few target trees from T2 and a few from T3).

Late target trees selection is theoretically more convenient (Table 7), since the starting time of production guarantees both a positive cash flow and a shorter payback period. However, late selection can only be carried out when there are enough target trees able to produce a sufficient amount of valuable timber assortments. This condition is not often met under most Turkey oak coppices in Central Italy.

Financial assessment of implementing the tree-oriented silvicultural scheme at a case-study level

Financial feasibility of the investment required for the implementation of the adopted silvicultural scheme was verified over an area of 12.5 hectares in a Turkey oak coppice in Grotte S. Stefano (Viterbo, Central Italy). Target trees selection was carried out at the end of the first coppice rotation (late selection). Early selection is then applied during subsequent coppice rotations, every 10 years. A transition period of 80 years was considered and wood production within the protective ring was estimated equal to 50% of customary coppice regime. The harvestable roundwood as a function of the transition time (years) is reported in Table 8. The first selection of target tree species has not taken advantage of the early silvicultural operations during the selection phase to get valuable timber assortments. Nevertheless, convenience indicators gave positive outcomes: R/C =1.01; IRR = 2.54%; NPV = 126 € ha^{-1}. Payback time is 100 years and the cash flow turns positive after 60 years (Table 8).

Table 6 - Financial indicators of the proposed tree-oriented silvicultural approach as a function of transition period length.

Duration of transition period (years)	R/C	IRR (%)	NPV (€ ha^{-1})	NPV (€ ha^{-1}) year^{-1})	Year when cash flow becomes positive	Payback period (years)
60	1.00	2.65	26.24	0.22	60	100
80	1.02	3.00	249.20	2.08	80	100

Table 7 - Financial indicators of the proposed tree-oriented silvicultural approach as a function of time of target tree selection.

Time of selection	R/C	IRR (%)	NPV (€ ha^{-1})	NPV (€ ha^{-1}) year^{-1})	Year when cash flow becomes positive	Payback period (years)
Early (T1 trees)	1.02	3.00	249.20	2.08	80	100
Medium Late (T2 trees)	1.07	4.30	730.68	6.09	60	60
Late (T2+T3 trees)	1.12	6.52	1.298.50	10.82	40	40

Discussion

This study showed that enhancing sporadic tree species able to produce valuable timber, coupled

Table 8 - Harvestable roundwood (expressed in m^{3}ha^{-1}) from the proposed tree-oriented silvicultural approach as a function of years from the first intervention (transition period) in the case-study (I = first timber quality class; II = second timber quality class; III = third timber quality class).

Tree species	Transition period (years)									
	40			60			80			100
	I	II	III	I	II	III	I	II	III	I
Service tree	0.02	0.06	0.02	0.31	0.21	0.42	3.50	1.70	0.67	2.98
Wild service tree					0.03	0.09		0.09	0.08	0.37
Wild apple		0.02					0.06			0.06
Field maple						0.14	0.22		0.08	0.22
Wild pear		0.02					0.15			0.10
Field helm				0.56	0.39	0.22	2.67	1.18	0.22	2.20

with coppice management, is more convenient than customary coppice management. Main advantages of the proposed tree-oriented silvicultural approach rely on the improvement of the property, on its profitability and low introduction costs, mainly due to a reduction of coppice revenues rather than of actual cash outflow.

The highest financial performances are guaranteed by silvicultural practices which largely maximize the revenue to cost balance, especially in the late selection of target trees (Fig. 2), rarely occurring anyway in the practice. On the other hand, the early selection of target trees represents the easiest silvicultural choice, and has the highest potential to yield valuable timber production at the end of the transition period, especially on fertile sites. In the early selection of target trees, however, the revenue to cost ratios are relatively low, which may limit the attractiveness of the investment in this silvicultural approach. Other critical issues linked to the introduction of the proposed tree-oriented approach in Turkey oak coppice silviculture are mainly referred to the: (i) operational costs for localized (target trees) silvicultural practices during coppice rotation; (ii) relatively long investment return time; (iii) market uncertainty, with possible substantial changes of the stumpage and market price of sporadic tree species timber. For these reasons, the financial support by European Union Common Agricultural Policy, and namely Rural Development Plans, is deemed desirable for allowing the implementation of tree- oriented silvicultural approach: particularly, the incentives could enable the intensification of silvicultural tending, mandatory to increase the technological quality of wood material.

Acknowledgements

This study was carried out under the project SELVALB "The tree silviculture to increase the value of forests in some areas of the territory of Tuscia", funded by Measure 124 "Cooperation for development of new products, processes and technologies in the agricultural sector, food and forestry" of the Rural Development Programme (RDP) 2007/2013 of the Lazio Region, Italy (concession Act no. 59/124/10 of 12.12.2014 - Question no. 8475921080 - recipient Department for Innovation in Biological systems, food and agriculture and Forestry (DIBAF), University of Tuscia in Viterbo). Francesco Chianucci was funded by the MiPAAF - Italian National Rural Network. Language translation from Italian to English was made by Nicolò Camarretta.

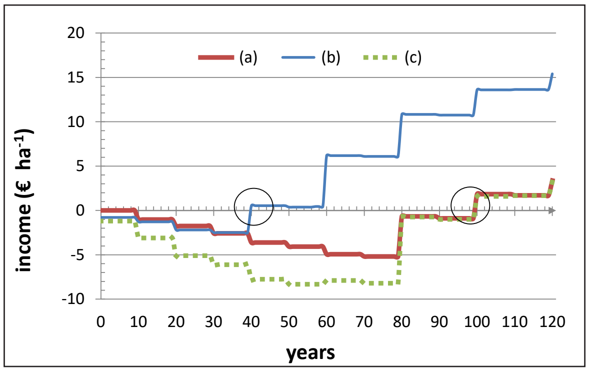

Figure 2 - Cash flow and payback period (circles) according to the proposed tree-oriented silvicultural approach with respect to the cases described Table 7 (a = early selection of the target trees; b = late selection of target trees) and at Table 8 (c).

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