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SHORT-TERM IMPACT OF COPPICE MANAGEMENT ON SOIL IN A *QUERCUS ILEX* L. STAND OF SARDINIA

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ABSTRACT

The short-term impact of coppice-with-standards management on soil in a Mediterranean holm oak forest was assessed to contribute to address appropriate recommendations to minimize possible negative effects of the silvicultural practices. For this purpose, soil surface features and topsoil properties were investigated in two representative areas located in a public forest in southwest Sardinia (Italy) and coppiced in the periods November 2012–March 2013 and November 2011–March 2012, respectively. Regardless of differences in soils and slope gradient, the same management, in terms of final density of trees standing after the clear-cut and accumulation of brushwood in strips along the maximum slope gradient, was applied in both areas. Field observations and laboratory data highlighted the disturbances caused to the soil by the silvicultural practices in the stands when compared with the undisturbed stands. These disturbances involved the almost complete removal of organic horizons, with consequent negative impact on organic carbon content, and the activation of erosion processes, mostly related to rainsplash erosion. Although soil mobilization locally largely exceeded the tolerable erosion rates, no extreme rainfall events occurred after the coppicing to produce critical situations at the catchment level. The adjustment of the final density of trees standing after the clear-cut in relation to soil properties, slope gradient and the possibility of extreme rainfall events, a different brushwood management and the restriction to the passage of wild animals would have strongly reduced the negative impacts on soils. © 2016 The Authors. *Land Degradation and Development* published by John Wiley & Sons, Ltd.

KEY WORDS: coppice-with-standards (CWS); Mediterranean holm oak forests; soil; organic horizons; soil erosion

INTRODUCTION

Forest management is a worldwide topical issue as it can cause considerable environmental and socio-economic impacts (Keesstra, 2007; Keesstra *et al.*, 2009; Belay *et al.*, 2015; Bruun *et al.*, 2015; Jacob *et al.*, 2015; MacDicken *et al.*, 2015; Tilahun *et al.*, 2015). Following the Forest Principles (UN, 1992), sustainable forest management has been encouraged as an important guiding principle in managing forests (EC, 2003; ITTO, 2006). The concept provides guidance on how to manage forests to provide for today's needs (as best as possible) while maintaining ecological functions of healthy forest ecosystems as not to compromise (i.e. reduce) the options of future generations (MacDicken *et al.*, 2015; Brandt *et al.*, 2016). Similar concepts are valid for soil as well (Keesstra *et al.*, 2016).

Despite the traditional claim that coppicing plays a major role in erosion control (Scarascia-Mugnozza *et al.*, 2000), several national and international studies highlighted the necessity of effective conservation practices to mitigate the post-harvesting impacts on the ecological forest cycles (Dissmeyer & Foster, 1984; Edeso *et al.*, 1999; Iovino, 2009). Indeed, the biomass removal may possibly have undesirable impacts on soil functions, water cycle, site productivity, biodiversity and atmospheric systems (Williams, 2003; Lattimore *et al.*, 2009; Ojea *et al.*, 2012; Gamfeldt *et al.*, 2013). As far as soil is concerned, organic matter depletion (Rubio & Escudero, 2003; Noormets *et al.*, 2015), nutrient losses (Ranger & Nys, 1996; Pyttel *et al.*, 2015; Šrámek *et al.*, 2015), changes in bulk density or porosity (Worrell & Hampson, 1997; Cambi *et al.*, 2015) and accelerated erosion (Swanston & Swanson, 1976; Derose *et al.*, 1993; Greer *et al.*, 1996; Kitahara *et al.*, 2000; Stott *et al.*, 2001; Borrelli & Schütt, 2014; Borrelli *et al.*, 2016) are the most detected negative impacts. As regards this latter impact, the importance of the interaction between vegetation cover and soil erosion has been highlighted by many studies (Cerdà, 1998; Feng *et al.*, 2015; Ola *et al.*, 2015). However, some reports have presented indifferent or positive effects of coppicing on soil conditions (Hölscher *et al.*, 2001; Pignataro *et al.*, 2011; Kupec *et al.*, 2015). Moreover, it is important to highlight that despite the widespread use of coppice management in Mediterranean xeric conditions (Scarascia-Mugnozza *et al.*, 2000), to the best of our knowledge, only very few studies focus on field observations of the impact on soil in these areas.

The growing demand for energy and raw materials, together with climate change and globalization, is predicted to result in increased demand for forest resources in the European countries (UNECE/FAO *et al.*, 2010). In this context, the European Union (EU) has set an ambitious target to achieve 20% of energy sourced from renewables by 2020 (EU (European Union), 2009). According to EUROSTAT

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(2014), in 2012, about 97 million m^3 of fuelwood was harvested in the European Union 28 nations, with about 5·38 million m^3 harvested in Italy.

In Sardinia (Italy), according to preliminary data from air photo interpretation for the Third National Forest Inventory (MiPAF (Ministero delle Politiche Agricole Alimentari e Forestali), 2007), forestland (woods, different types of maquis and bushes) covers about 12,414 km^2 or 51% of the island's surface. A previous inventory accounts for about 5,834 km^2 of woods, of which about 9% were managed as simple coppice with about 12% managed as coppice-with-standards (CWS) (RAS, 2007), a silvicultural system where some trees among the coppice, called 'standards', are left to grow to a larger timber size. As a result, a large part of the island, mostly in vulnerable mountainous landscapes that are highly sensitive to environmental changes, is subject to anthropogenic disturbance (Aru *et al*., 2006).

Holm oak (*Quercus ilex* L.) coppice stands of Sardinia were exploited and strongly modified in the past, mainly because of grazing and firewood and charcoal production, but in the last decades, the abandonment of farmlands, the use of fossil fuels and, more recently, the increasing importance of forest ecosystems as a source of environmental benefits led to the cessation of the coppice system in large areas (Cutini & Mascia, 1998). Only very recently, EU sustainable energy policies driving massive demand for new energy commodities have restarted the interest in coppicing. Public awareness of the consequences is evident from newspaper articles and parliamentary debates.

This study aimed to assess the short-term impact on soil of the CWS management applied in the holm oak public forest of Marganai (south Sardinia). The results obtained may improve our knowledge about the response to this type of management of similar soils in Mediterranean holm oak forests and may allow to derive practical silvicultural recommendations to ensure that soil fertility can be sustained on sites where the resumption of coppicing is being considered.

MATERIALS AND METHODS

Study area and stand characteristics

The study area is located in southwest Sardinia, between 39° 23′50″ to 39°24′32″ N latitude and 8°35′27″ to 8°35′57″ E longitude, in the public holm oak forest of Marganai. Geology of the area mainly consists of Cambrian limestones and Ordovician metasiltites and metapelites, with subordinate metasandstones (RAS, 2010). Small outcrops of Carboniferous syenogranites and Holocene colluvial deposits are present as well (RAS, 2010). Elevation ranges from 660 to 820 m above sea level (asl), and slope gradient is between 14 and 55%. The predominant soils are Leptosols, Regosols and Cambisols formed by the alteration of the parent materials (Aru *et al*., 1991). The data of two meteorological stations may be considered as representative for the area under study. Average annual rainfall according to the data from the Montimannu station (350 m asl) for the period 1925–2014 is 1,056 mm, while according to the data from the Marganai station (721 m asl) for 2012–2014, it is 1,072 mm. Rainfall is concentrated in autumn and winter, with highest rainfalls generally occurring from October to March. No direct temperature data are available for the area. Extrapolation from other stations assigns around 13 °C as average annual temperature in the area.

From a phytosociological point of view, the study area falls in the suballiance *Clematido cirrhosae–Quercenion ilicis* (Bacchetta *et al*., 2004), with *Q. ilex* as dominant species and *Arbutus unedo*, *Phyllirea latifolia* and *Erica arborea* being the most common associated species. *Pistacia lentiscus*, *Phyllirea angustifolia* and *Myrtus communis* may be present in the warmest sites, while in more humid sites, *Viburnum tinus* appears. *Ilex aquifolium* is generally present in the coolest sites (north and northeast aspects at higher elevation). The coppice trees (mainly *Q. ilex*, *Arbutus unedo* and *Phyllirea latifolia*) have grown naturally without any pruning since the last timber harvesting, approximatively in the 1940s. Between November 2010 and December 2013, in 34 ha, the tree vegetation was entirely harvested as CWS using the shelterwood technique (about 150 trees ha^{-1} standing after clear-cut). The brushwood was accumulated in strips along the maximum slope gradient and left in the field. The vegetation remaining in the undisturbed sites is a mixed forest of coppice trees similar to those in the harvested sites before cutting. Here, the tree density is approximately 4,000 trees ha^{-1}, and the tree heights range from 5 to 12 m with an average of 9·3 m.

Field survey

Following a reconnaissance survey, made to evaluate possible different geomorphological and vegetational conditions, two representative areas of about 1.5 ha each, respectively named S'Isteri and Su Caraviu, were selected for investigation in May 2015. These areas differ in geological substratum, soils and slope gradient. Coppicing at S'Isteri started in November 2012 and ended in March 2013, while at Su Caraviu, it started in November 2011 and ended in March 2012. In each area, one reference soil profile was opened and described, making a distinction in pedogenetic horizons according to standard procedures of soil description (Schoeneberger *et al*., 2012). Soils were sampled horizon-wise for standard analyses and classified according to IUSS Working Group WRB (2014).

Two types of survey design were used to assess the impact of coppice management on soil: free survey and survey by transects (Soil Survey Division Staff, 1993). Concerning the latter, in each area, nine control plots of 1 m^2 each (three located in the upper part of the slope, three in the middle part and three in the lower part) were identified in the CWS stand and three more, of the same size, in the adjacent undisturbed holm oak stand (one in the upper part of the slope, one in the middle part and one in the lower part) (Figure 1A and B). The control plots in the CWS stand were located between brushwood strips. The number of control plots is much lower in the undisturbed holm oak stand than in the CWS stand

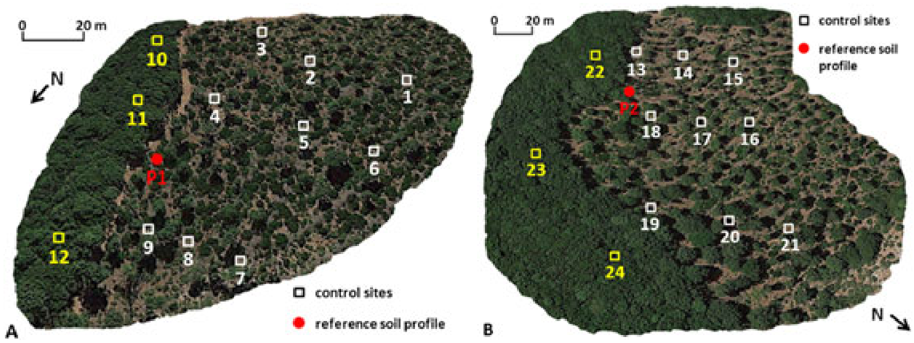

Figure 1. Control plots and reference soil profile locations at S'Isteri (A) and at Su Caraviu (B). Background images Google Earth image (date 26.07.2015). [Colour figure can be viewed at wileyonlinelibrary.com]

because, as detected during the reconnaissance and the free surveys, in the former, the situation is much more homogenous than in the latter and soil erosion is completely absent. The following observations and measurements were made in each control plot: slope gradient, surface stoniness, twigs on the ground surface, microrelief, presence/absence of organic horizons, structure of the upper mineral horizon, sequence of mineral horizons in the topsoil (upper 20–25 cm), evidence of erosion and deposition processes, topsoil (upper 6 cm) bulk density, topsoil (upper 6 cm) moisture content and infiltration rate. Soil surface features and topsoil properties were described according to Schoeneberger *et al.* (2012), except for the organic horizons that were designed according to Jabiol *et al.* (2013). Accelerated erosion and deposition processes were detected by visual assessment (USDA, 1996; McGarry, 2004; Houšková, 2006), mainly considering exposed roots, rock outcrops, isolated pedestals, rills and mounds. Undisturbed topsoil (upper 6 cm) core samples for the determination of bulk density and moisture content were collected using a stainless metal ring with a volume of 100 cm^3 (Eijkelkamp, the Netherlands). To assess the hydrological behaviour of the soils in the study sites, rapid measurements of infiltration rate were performed by a single-ring infiltrometer (Nimmo *et al.*, 2009) with a diameter of 152 mm, considering the time needed to infiltrate an amount of water equal to 110 mm of rain, corresponding to the most frequent rain intensity over 100 mm per day measured since 1925 in the area. Samples of organic horizons and upper mineral horizons were collected for organic carbon (OC) determination. Vegetation characteristics around each plot were also recorded. As regards the free survey, it was aimed to detect the presence/absence of erosion and deposition processes using the same methodology described earlier. The free survey covered about 16,000 m^2 in each area.

Soil analysis

The physical and chemical soil properties were determined according to the procedures published by the Ministero delle Politiche Agricole e Forestali (MiPAF, 1998, 2000). The bulk soil samples were air dried and sieved to <2 mm. Sand (2·00–0·05 mm), silt (0·050–0·002 mm) and clay (<0·002 mm) fractions were separated after the removal of organic matter by H_2O_2 treatment and dispersion aided by Na-hexametaphosphate by the sieve and pipette methods. The OC content was determined by C elementary analyser (Leco, USA). Bulk density (dry weight per unit volume) and moisture content were obtained from the undisturbed topsoil core samples determining the weight after drying.

Rainfall data

Daily rainfall data from the Montimannu station (350 m asl) for January 1925 to April 2014 were analysed to extrapolate the days with rainfall ≥50 mm. This value was used to represent heavy rainfall events (Bodini & Cossu, 2010). As for the Marganai station (721 m asl) hourly rainfall data were available for January 2012 to April 2015, dates with rainfall ≥50 mm in 24 h were extrapolated. The hours with rainfall ≥10 mm, approaching the threshold to shift the erosion process from the transport-limited to the detachment-limited phase (Abu Hammad *et al.*, 2006), were detected as well.

Statistical analysis

Statistical analyses were conducted with STATISTICA 10.0 (StatSoft Inc., Tulsa, OK, USA). The Kruskal–Wallis test was utilized to identify significant differences in the data set on a 0·05 level after an explorative data analysis. The content of organic carbon in identified organic horizons and topsoil layers was calculated as total mass per m^2. The descriptive information on erosion/deposition features on nominal scale was transferred into ordinal scale with none feature = 1, deposition with soil material coming from upslope = 2, exposed roots = 3 and rill occurrence = 4.

RESULTS

Mineral soils at S'Isteri are derived from Holocene colluvial deposits, are deeper than 1 m and are characterized by an A-Bw1-Bw2-C profile, sandy loam texture in the A horizon and loam texture in the Bw horizons, subangular blocky structure and an organic carbon content of 54·3 g kg^{-1} in the A horizon. Although the increase in clay with depth (from 138 g kg^{-1} in the A horizon to 254 g kg^{-1} in the Bw2 horizon), no clay coatings have been identified, and these soils have been classified as

Chromic Cambisols. Dominant mineral soils at Su Caraviu are derived from Cambrian limestones, Ordovician metasiltites and metapelites and their Holocene colluvial deposits, are from shallow to moderately deep and are characterized by an A1-A2-A3-R profile, silt loam texture in the A1 horizon and loam texture in the A2 and A3 horizons, subangular blocky structure and an organic carbon content of 26·1 g kg^{-1} in the A1 horizon. These soils have been classified as Leptic Phaeozems. Leptosols, characterized by an A-R profile and with continuous rock starting at a depth ≤ 25 cm from the mineral soil surface, are present as inclusions.

Field observations and laboratory data concerning the control plots at S'Isteri are shown in Tables I and II. Slope gradient varies between 14 and 42%, with lowest values in the upper part of the slope. Tree cover around the control plots in the CWS stand is generally between 2 and 5%, with the exception of plot 6 where it is absent, while shrub cover generally varies between 70 and 93%, with the exception of plot 7 where it is 20%. In the undisturbed holm oak stand (plots 10 to 12), the tree cover is 100%. Tree renewal by seedlings is always absent. Fallen trees are sometimes present. Surface stoniness varies between 0 and 25%, with highest values in the CWS stand. Twigs cover 1 to 20% of the plot surface, with highest values in the CWS stand. The microrelief is almost always characterized by undulations due to wild boar rooting. These undulations are generally much deeper in the CWS stand than in the undisturbed holm oak stand. A complete sequence of organic horizons is always present in the undisturbed stand, while in the CWS stand, organic horizons are missing or are limited to the presence of a thin to very thin scattered OL horizon. The topsoil mineral horizon is loose in plots 1 to 5 because of wild boar rooting, while in the other plots it presents a subangular blocky structure. In three out of the nine plots in the CWS stand there is deposition with soil material coming from upslope (where roots are exposed), while in one plot (plot 4) exposed roots are present. Topsoil (upper 6 cm) bulk density ranges between 0·50 and 1·12 g cm^{-3},

Table I. Slope gradient, vegetation characteristics and surface characteristics in control plots at S'Isteri

Plot	SG %	Vegetation around the plot	SS %	T %	Microrelief
1	27	tree cover 2–5% (mainly *Quercus ilex* with some *Ilex aquifolium*), shrub cover 70% (*Arbutus unedo*, *Cistus monspeliensis* and *Erica arborea*), absence of tree renewal by seedlings	2	20	undulations (max depth 11 cm, max width 35 cm) due to wild boar rooting
2	25	tree cover 2–5% (mainly *Quercus ilex* with some *Ilex aquifolium*), shrub cover 85% (*Arbutus unedo*, *Cistus monspeliensis* and *Erica arborea*), absence of tree renewal by seedlings	10	5	undulations (max depth 8 cm, max width 7 cm) due to wild boar rooting
3	21	tree cover 2–5% (mainly *Quercus ilex* with some *Ilex aquifolium*), shrub cover 85% (*Arbutus unedo*, *Cistus monspeliensis* and *Erica arborea*), absence of tree renewal by seedlings, presence of fallen trees	3	3	undulations (max depth 5 cm, max width 10 cm) due to wild boar rooting
4	38	tree cover 2–5% (mainly *Quercus ilex* with some *Ilex aquifolium*), shrub cover 93% (*Arbutus unedo*, *Cistus monspeliensis* and *Erica arborea*), absence of tree renewal by seedlings	10	2	undulations (max depth 7 cm, max width 15 cm) due to wild boar rooting
5	36	tree cover 1–2% (mainly *Quercus ilex* with some *Ilex aquifolium*), shrub cover 75% (*Arbutus unedo*, *Cistus monspeliensis* and *Erica arborea*), absence of tree renewal by seedlings	10	5	undulations (max depth 4 cm, max width 10 cm) due to wild boar rooting
6	38	shrub cover 75% (*Arbutus unedo* and *Crataegus monogyna*), absence of tree renewal by seedlings, presence of fallen trees	7	20	undulations (max depth 12 cm, max width 18 cm) due to wild boar rooting
7	36	tree cover 2–3% (mainly *Quercus ilex* with some *Ilex aquifolium*), shrub cover 20% (*Arbutus unedo*, *Cistus monspeliensis* and *Erica arborea*), absence of tree renewal by seedlings	20	3	undulations (max depth 3 cm, max width 20 cm) due to wild boar rooting
8	36	tree cover 2% (*Quercus ilex*), shrub cover 70% (*Arbutus unedo* and *Erica arborea*), absence of tree renewal by seedlings	25	1	undulations (max depth 10 cm, max width 30 cm) due to wild boar rooting
9	36	tree cover 2% (mainly *Quercus ilex* with some *Ilex aquifolium*), shrub cover 85% (*Arbutus unedo*), absence of tree renewal by seedlings	10	2	undulations (max depth 18 cm, max width 40 cm) due to wild boar rooting
10	14	tree cover 100% (mainly *Quercus ilex* with some *Arbutus unedo* and *Phyllirea latifolia*) with average height of 9·5 m, absence of tree renewal by seedlings	0	4	undulations (max depth 2 cm, max width 10 cm) due to wild boar rooting
11	32	tree cover 100% (mainly *Quercus ilex* with some *Arbutus unedo*, *Erica arborea* and *Ilex aquifolium*) with average height of 6 m, absence of tree renewal by seedlings	0	2	flat
12	42	tree cover 100% (mainly *Quercus ilex* with some *Arbutus unedo*, *Erica arborea* and *Ilex aquifolium*) with average height of 8·5 m, absence of tree renewal by seedlings	3	3	undulations (max depth 5 cm, max width 15 cm) due to wild boar rooting

SG, slope gradient; SS, surface stoniness; T, twigs.

Table II. Soil horizons, erosion/deposition features and topsoil data in control plots at S'Isteri

Plot	Organic horizons	Topsoil mineral horizons	Erosion/deposition features	BD g cm^{-3}	MC %	OC g kg^{-1}	IR cm h^{-1}
1	OL (0·5 to 2 cm thick) in 50% of the plot surface	loose Ap (2 cm thick), over very fine sbk A2 (2 cm thick), over medium to coarse sbk Bw (>16 cm thick)	none	0·96	12·48	75 (Ap + A2)*	660·0
2	OL (1 cm thick) in 5% of the plot surface	loose Ap (2 cm thick), over very fine sbk A2 (2 cm thick), over medium to coarse sbk Bw (>16 cm thick)	none	0·83	8·79	100 (Ap + A2)	198·0
3	OL (1 cm thick) in 2% of the plot surface	loose Ap (2 cm thick), over very fine sbk A2 (2 cm thick), over medium to coarse sbk Bw (>16 cm thick)	none	0·46	13·93	176 (Ap + A2)	262·2
4	none	loose Ap (2 cm thick), over very fine sbk A2 (2 cm thick), over medium to coarse sbk Bw (>16 cm thick)	exposed roots in 4% of the plot due to passage of ungulates and wild boar rooting	1·02	7·44	89 (Ap + A2)	45·5
5	none	loose Ap (2 cm thick), over very fine sbk A2 (2 cm thick), over medium to coarse sbk Bw (>16 cm thick)	none	1·12	10·44	94 (Ap + A2)	18·4
6	none	fine sbk A (6 cm thick), over medium to coarse sbk Bw (>16 cm thick)	deposition with soil material coming from upslope (where roots are exposed)	0·73	10·91	120 (A)	220·0
7	OL (0·2 cm thick) in 3% of the plot surface	fine sbk A (8 cm thick), over medium to coarse sbk Bw (>14 cm thick)	deposition with soil material coming from upslope (where roots are exposed)	0·78	10·92	87 (A)	188·6
8	none	fine sbk A1 (10 cm thick), over medium to coarse sbk A2 (>12 cm thick)	none	0·50	28·05	160 (A1)	360·0
9	none	fine sbk A (15 cm thick), over medium to coarse sbk Bw (>10 cm thick)	deposition with soil material coming from upslope (where roots are exposed)	0·82	6·35	76 (A)	792·0
10	OL (4 cm thick), over OF (0·3 cm thick), over OH (0·3 cm thick)	very fine to fine sbk A (3 cm thick), over coarse to very coarse sbk Bw (>20 cm thick)	none	0·72	17·74	409 (OL) 223 (OF) 203 (OH) 89 (A)	183·3
11	OL (3 cm thick), over OF (0·2 cm thick), over OH (1 cm thick)	medium sbk A (4 cm thick), over medium to coarse sbk Bw (>20 cm thick)	none	0·83	11·07	441 (OL) 299 (OF) 221 (OH) 120 (A)	94·3
12	OL (1 cm thick), over OF (0·3 cm thick), over OH (0·3 cm thick)	very fine to fine sbk A (3 cm thick), over coarse to very coarse sbk Bw (>20 cm thick)	none	0·66	15·81	433 (OL) 405 (OF) 203 (OH) 146 (A)	360·0

BD, topsoil (upper 6 cm) bulk density; MC, topsoil (upper 6 cm) moisture content; OC, organic carbon; IR, infiltration rate.
*Between brackets is the horizon code.

with lowest and highest values in the CWS stand. Topsoil (upper 6 cm) moisture content ranges between 6·35 and 28·05% in the CWS stand and between 11·07 and 17·74% in the undisturbed holm oak stand. The OC content strongly depends on the presence/absence of organic horizons. The infiltration rate generally ranges between 183·3 and 792·0 cm h^{-1}, with the exception of two plots (4 and 5) in the CWS stand, with 45·5 and 18·4 cm h^{-1}, and one plot (11) in the undisturbed stand, with 94·3 cm h^{-1}. Variations may be related to changes in bulk density, stoniness below surface and clay content in the topsoil. Indeed, highest values of bulk density and clay content (254 g kg^{-1}) for the area were recorded at plots 4 and 5.

The free survey in the CWS stand at S'Isteri highlighted the presence of very frequent erosion and deposition features such as exposed roots (Figure 2A–C), splash pedestals (Figure 2D), exposed rock fragments (Figure 2E), rills (Figure 2F) and mounds of soil material coming from upslope (Figure 2G). Anyhow, as rills did not join up to form a dynamic ephemeral drainage network, transport and deposition processes were

Figure 2. Examples of erosion and deposition features in the CWS stand (A–G) and forest floor at the undisturbed stand (H) at S'Isteri. Exposed roots (A–C), splash pedestals (D), exposed rock fragments (E), rill erosion (F), mound of soil material coming from upslope (G) and forest floor (H). [Colour figure can be viewed at wileyonlinelibrary.com]

confined within the slope zone, not affecting downslope areas. No erosion or deposition features were detected in the undisturbed holm oak stand (Figure 2H). Moreover, the free survey in the CWS stand confirmed the very limited tree renewal by seedlings and the almost complete absence of organic horizons and highlighted the presence of 12% fallen *Q. ilex* trees and about 26% fallen *I. aquifolium* trees. Furthermore, the standing *I. aquifolium* trees were seriously damaged by the browsing and bark-stripping of local deer (*Cervus elaphus corsicanus*).

Field observations and laboratory data concerning the control plots at Su Caraviu are shown in Tables III and IV. Slope gradient varies between 32 and 55%, with lowest values in the lower part of the slope. Tree cover around the control plots in the CWS stand ranges between 2 and 55%, while shrub cover varies between 30 and 85%. In the undisturbed holm oak stand (plots 22 to 24), the tree cover is 100%. Tree renewal by seedlings is only present in plots 14 and 24. Fallen trees are only present around plots 13 and 15. Surface stoniness varies between 0 and 20%, with highest values in the CWS stand. Twigs cover 1 to 5% of the plot surface. The microrelief is almost always characterized by undulations due to wild boar rooting. These undulations are generally deeper in the CWS stand than in the undisturbed holm oak stand. Organic horizons are always present in the undisturbed stand, while in the CWS stand, they are missing or are limited to the presence of a thin to very thin scattered OL horizon, with the exception of plot 15 where a 2-cm thick OF

Table III. Slope gradient, vegetation characteristics and surface characteristics in control plots at Su Caraviu

Plot	SG %	Vegetation around the plot	SS %	T %	Microrelief
13	40	tree cover 10% (mainly *Quercus ilex* with some *Ilex aquifolium*), shrub cover 35% (*Arbutus unedo*, *Cistus monspeliensis* and *Cistus incanus*), absence of tree renewal by seedlings, presence of fallen trees	20	2	undulations (max depth 10 cm, max width 40 cm) due to wild boar rooting
14	55	tree cover 2% (mainly *Quercus ilex* with some *Phyllirea latifolia*), shrub cover 30% (*Arbutus unedo*, *Cistus monspeliensis* and *Erica arborea*), signs of renewal of *Quercus ilex* by seedlings	3	3	undulations (max depth 7 cm, max width 20 cm) due to wild boar rooting
15	36	tree cover 2% (*Ilex aquifolium*), shrub cover 30% (*Arbutus unedo*, *Erica arborea and Cistus monspeliensis*), absence of tree renewal by seedlings, presence of fallen trees	5	2	undulations (max depth 4 cm, max width 20 cm) due to wild boar rooting
16	51	tree cover 3% (mainly *Quercus ilex* with some *Crataegus monogyna*, *Phyllirea latifolia* and *Ilex aquifolium*), shrub cover 85% (*Arbutus unedo*, *Cistus incanus* and *Erica arborea*), absence of tree renewal by seedlings	3	1	undulations (max depth 3 cm, max width 20 cm) due to wild boar rooting
17	47	tree cover 4% (mainly *Quercus ilex* with some *Ilex aquifolium*), shrub cover 80% (*Arbutus unedo*, *Cistus monspeliensis*, *Erica arborea* and *Phyllirea latifolia*), absence of tree renewal by seedlings	10	2	undulations (max depth 6 cm, max width 20 cm) due to wild boar rooting
18	51	tree cover 40% (mainly *Quercus ilex* with some *Ilex aquifolium*), shrub cover 85% (*Arbutus unedo*), absence of tree renewal by seedlings	2	2	undulations (max depth 6 cm, max width 35 cm) due to wild boar rooting
19	47	tree cover 55% (mainly *Quercus ilex* with some *Ilex aquifolium*), shrub cover 65% (*Arbutus unedo* and *Cistus monspeliensis*), absence of tree renewal by seedlings	5	5	undulations (max depth 10 cm, max width 40 cm) due to wild boar rooting
20	40	tree cover 15% (mainly *Quercus ilex* with some *Ilex aquifolium*), shrub cover 60% (*Arbutus unedo* and *Cistus monspeliensis*), absence of tree renewal by seedlings	5	1	undulations (max depth 5 cm, max width 25 cm) due to wild boar rooting
21	42	tree cover 55% (mainly *Quercus ilex* with some *Ilex aquifolium*), shrub cover 85% (*Arbutus unedo*, *Cistus monspeliensis*, *Erica arborea* and *Phyllirea latifolia*), absence of tree renewal by seedlings	7	2	undulations (max depth 9 cm, max width 40 cm) due to wild boar rooting
22	36	tree cover 100% (mainly *Quercus ilex* with some *Arbutus unedo* and *Ilex aquifolium*) with average height of 10 m, absence of tree renewal by seedlings	0	5	undulations (max depth 2 cm, max width 10 cm) due to wild boar rooting
23	34	tree cover 100% (mainly *Quercus ilex* with some *Arbutus unedo*, *Erica arborea* and *Ilex aquifolium*) with average height of 12 m, absence of tree renewal by seedlings	3	2	undulations (max depth 7 cm, max width 20 cm) due to wild boar rooting
24	32	tree cover 100% (mainly *Quercus ilex* with some *Arbutus unedo*, *Erica arborea* and *Ilex aquifolium*) with average height of 11 m, some tree renewal by seedlings	3	3	undulations (max depth 7 cm, max width 20 cm) due to wild boar rooting

SG, slope gradient; SS, surface stoniness; T, twigs.

horizon covers 50% of the plot. The topsoil mineral horizon is partially loose because of wild boar rooting in three out of the nine plots in the CWS stand, while in all other cases it presents a subangular blocky structure. Erosion features are present in five out of the nine plots in the CWS stand, while in one plot (plot 19) there is deposition with soil material coming from upslope (where roots are exposed). Topsoil (upper 6 cm) bulk density ranges between 0·45 and 0·94 g cm^{-3}. Topsoil (upper 6 cm) moisture content ranges between 4·90 and 12·97% in the CWS stand and between 14·50 and 22·05% in the undisturbed holm oak stand. The organic carbon content strongly depends on the presence/absence of organic horizons. The infiltration rate generally ranges between 134·7 and 792·0 cm h^{-1}, with the exception of plot 19 with 37·7 cm h^{-1}. Variations may be related to changes in bulk density, stoniness below surface and clay content in the topsoil.

As for S'Isteri, the free survey in the CWS stand at Su Caraviu highlighted the presence of very frequent erosion and deposition features such as exposed roots (Figure 3A and B), isolated pedestals (Figure 3C and D), rock outcrops (Figure 3E and F) and mounds of soil material coming from upslope (Figure 3G). Anyhow, as rills did not join up to form a dynamic ephemeral drainage network, transport and deposition processes were confined within the slope zone, not affecting downslope areas. No erosion or deposition features were detected in the undisturbed holm oak stand (Figure 3H). Moreover, the free survey in the CWS stand confirmed the very limited tree renewal by seedlings and the almost complete absence of organic horizons and highlighted the presence of 5% fallen *Q. ilex* trees and about 51% fallen *I. aquifolium* trees. Furthermore, the standing *I. aquifolium* trees were seriously damaged by the browsing and bark-stripping of local deer.

Table IV. Soil horizons, erosion/deposition features and topsoil data in control plots at Su Caraviu

Plot	Organic horizons	Topsoil mineral horizons	Erosion/deposition features	BD g cm^{-3}	MC %	OC g kg^{-1}	IR cm h^{-1}
13	none	loose to very fine and fine sbk Ap (8 cm thick), over very fine to fine sbk A2 (>17 cm thick)	none	0·92	5·60	65 (Ap)*	258·8
14	none	loose to very fine sbk Ap (3 cm thick), over medium to coarse sbk A2 (9 cm thick), over R layer	exposed roots in the all plot and shallow R layer	0·69	7·10	117 (Ap + A2)	134·7
15	OF (2 cm thick) in 50% of the plot	fine to medium sbk A1 (15 cm thick), over medium sbk A2 (>10 cm thick)	exposed roots in 10% of the plot	0·93	4·90	78 (A1)	180·8
16	OL (0·1 cm thick) in 5% of the plot	fine to medium sbk A1 (6 cm thick), over medium to coarse sbk A2 (>19 cm thick)	exposed roots in 20% of the plot	0·94	6·40	58 (A1)	201·0
17	none	fine to medium sbk Ap (6 cm thick), over medium sbk A2 (>19 cm thick)	exposed roots in 5% of the plot	0·63	12·97	111 (Ap)	282·9
18	OL (0·1 cm thick) in 3% of the plot	loose to fine and medium sbk Ap (2–6 cm thick), over medium to coarse sbk A2 (>19 cm thick)	one rill crossing the plot	0·66	11·94	91 (Ap)	267·6
19	OL (0·1 cm thick) in 2% of the plot	fine to medium sbk Ap (3–6 cm thick), over fine to medium sbk A2 (>19 cm thick)	deposition with soil material coming from upslope (where roots are exposed and rills are visible)	0·62	8·17	102 (Ap)	37·7
20	none	medium sbk A1 (5–8 cm thick), over fine sbk A2 (>17 cm thick)	none	0·86	8·41	87 (A1)	172·2
21	none	medium sbk Ap (4–8 cm thick), over fine to medium sbk A2 (>17 cm thick)	none	0·67	12·63	124 (Ap)	792·0
22	OL (3 cm thick), over OF (0·3 cm thick), over OH (2 cm thick)	very fine to fine sbk A (>25 cm thick)	none	0·61	14·50	388 (OL) 224 (OF) 205 (OH) 93 (A)	203·1
23	OL (2–3 cm thick), over OH (4–5 cm thick)	very fine to medium sbk A1 (6 cm thick), over fine to medium sbk A2 (>19 cm thick)	none	0·69	15·74	401 (OL) 202 (OH) 93 (A1)	416·8
24	OL (4 cm thick), over OF (1 cm thick), over OH (4 cm thick)	very fine to fine sbk A (8 cm thick), over fine sbk Bw (>17 cm thick)	none	0·45	22·05	416 (OL) 286 (OF) 215 (OH) 136 (A)	165·0

BD, topsoil (upper 6 cm) bulk density; MC, topsoil (upper 6 cm) moisture content; OC, organic carbon; IR, infiltration rate.
*Between brackets is the horizon code.

Table V depicts the Kruskal–Wallis test and shows the statistical differences between CWS plots and undisturbed plots for the entire set of data and the two sites, respectively. Because of coppicing, significant differences occur for tree and shrub density. As regards the entire set of data, significant differences at $<0{\cdot}05$ also exist for the parameters soil moisture, organic carbon content, erosion/deposition features and stoniness. There is no statistical significant difference in the measured infiltration rates and in the twigs presence at surface. Significant differences at $<0{\cdot}05$ at S'Isteri can be demonstrated, aside tree and shrub cover, only for organic carbon content and stoniness. A higher number of parameters show significant differences at the Su Caraviu site, indicating a higher sensitivity of this site to coppicing.

As regards rainfall data, 185 days with rainfall $\geq$50 mm were detected at the Montimannu station in the period of time

Figure 3. Examples of erosion and deposition features in the CWS stand (A–G) and forest floor at the undisturbed stand (H) at Su Caraviu. Exposed roots (A and B), isolated pedestals (C and D), rock outcrops (E and F), mound of soil material coming from upslope (G) and forest floor (H). [Colour figure can be viewed at wileyonlinelibrary.com]

from January 1925 to April 2014 (Figure 4A). Among these, 19 days with rainfall ≥100 mm were detected. From November 2011, start of coppicing in the studied areas, there were 15 days with rainfall ≥50 mm, two of which with rainfall ≥100 mm. At the Marganai station, in the period of time from January 2012 to April 2015, six dates with rainfall ≥50 mm in 24 h were recorded (Figure 4B), while the dates with hourly rainfall ≥10 mm amounted to 23 (Figure 4C).

DISCUSSION

Regardless of differences in soils and slope gradient, the same CWS management was applied in both studied areas, resulting in the same final density of trees standing after the clear-cut (about 150 trees ha^{-1}) and the same accumulation of brushwood in strips along the maximum slope gradient.

As it was to be expected, the CWS management applied in the holm oak public forest of Marganai produced the almost complete removal of organic soil horizons. Indeed, these horizons, together with the upper mineral horizon, are those immediately affected by drastic land use changes, while the subsurface mineral horizons commonly react over a longer period of time (Vacca, 2000). The loss of organic soil horizons inevitably means that in both areas there is a major difference in the organic carbon content of soils between the coppiced and undisturbed plots. According to

Table V. Kruskal–Wallis *p*-values; comparison of CWS plots with undisturbed plots for both investigation sites and for each site separated

	All CWS plots versus all undisturbed plots	CWS plots versus undisturbed plots at S'Isteri	CWS plots versus undisturbed plots at Su Caraviu
Bulk density	*0·0590*	0·4588	*0·0955*
Moisture	**0·0047**	0·1160	**0·0126**
Organic C content	**0·0047**	**0·0096**	**0·0096**
Infiltration rate	0·8676	0·5784	0·7815
Tree cover	**0·0003**	**0·0099**	**0·0116**
Shrub cover	**0·0003**	**0·0111**	**0·0112**
Erosion/depositon features	**0·0244**	0·1824	*0·0699*
Slope	*0·0693*	0·7770	**0·0155**
Stoniness	**0·0168**	**0·0234**	*0·0710*
Twigs	0·5119	0·6380	0·1573

p-values in bold indicate significant differences at <0·05.
p-values in italic indicate significant differences at <0·1.

Mallik & Hu (1997), the physical disturbance of soil and mixing of the litter layer with surface soil during harvesting result in significant redistribution of C between different pools and trigger accelerated carbon losses. In this regard, recent studies (Noormets *et al*., 2015 and references therein) show that the dynamics and processing of soil C in managed forests may produce a twofold reduction of the long-term carbon sequestration in soils with respect to unmanaged forests. Fallen trees represent a further soil surface disturbance at both S'Isteri and Su Caraviu.

Wild boar could move more easily in the CWS stands and with their rooting activity they often produced a loose Ap horizon. Consequently, the aggregate stability in this uppermost mineral horizon was nil, despite the high organic carbon content that, in normal conditions, acts as a cementing agent between the mineral particles, thereby increasing aggregate stability (Govers *et al*., 1990) and mitigating the soil erodibility (Torri *et al*., 1997). As regards soil erodibility, the generally low amount of clay in the uppermost mineral horizon of soils at S'Isteri and Su Caraviu results in low cohesion and, consequently, in low aggregate stability as well (Torri *et al*., 1997).

The generally low to very low topsoil bulk density values testify for a high porosity (Brady & Weil, 2008) and are coherent with the generally very high infiltration rate ($\geq$36·0 cm h^{-1}) measured in both areas. Topsoil bulk density values and infiltration rate did not show significant differences between the CWS stand and the undisturbed holm oak stand in both areas, indicating that erosion processes differ mainly because of more pronounced rainsplash effects in the CWS sites and less because of surface runoff generation.

S'Isteri has moderately steep to steep slopes (sensu Soil Survey Division Staff, 1993), ranging from 14 to 42%, while Su Caraviu is characterized by steep to very steep slopes (sensu Soil Survey Division Staff, 1993), ranging from 32 to 55%. It follows that the topography of the study sites has a propensity to encourage rain-induced erosion processes, which tend to increase as the slope gradient increases (Mahmoodabadi & Arjmand Sajjadi, 2016). In this regard, the situation at Su Caraviu is more critical than at S'Isteri. Available rainfall data show that heavy rainfall events ($\geq$50 mm) are not rare in the area and that sometimes the hourly intensity of rain may approach or exceed the threshold to shift the erosion process from the transport-limited to the detachment-limited phase. Indeed, the visual assessment of erosion and deposition features revealed a frequent soil mobilization in the CWS stands. The field observations prompt the hypothesis that rainsplash erosion has a greater impact than the wash-out process. In this regard, typical micromorphological features suggesting rainsplash erosion, such as splash pedestal formation and increased surface stoniness, could be observed across the entire CWS stands. This is consistent with the findings of Van Asch (1983) and Borrelli & Schütt (2014) in disturbed mountainous forests of south and central Italy. These authors stated that the rainsplash effect plays a dominant role for upland erosion in such environments. Rainsplash erosion in the CWS stands may be ascribed primarily to the lack of canopy cover, to the lack or very limited presence of organic horizons, to the very often loose condition of the topsoil and to a high rainfall kinetic energy. Moreover, the accumulation of brushwood in strips along the maximum slope gradient further increased the bare soil surface. By contrast, the dense vegetation of the undisturbed holm oak stands, characterized by a high rainfall interception capacity, in conjunction with a thick sequence of organic horizons, almost nullifies the detachment capacity of the incoming raindrops. The limited presence of wash-out processes may also be related to the absence of extreme rainfall events after the coppicing. Indeed, heavy precipitations with frontal origin, characterized by a high rainfall kinetic energy, regularly affect western Mediterranean countries during the late summer and autumn (Llasat *et al*., 2010; Tarolli *et al*., 2012). As an example, 517·4 mm of daily rainfall was recorded in December 2004 in central-east Sardinia (De Waele *et al*., 2010); 577 mm of rainfall in 12 h and 372 mm in 6 h were recorded in November 1999 and in October 2008, respectively, in south-west Sardinia (Cittadini *et al*., 2010); and 469·6 mm of daily rainfall, with 109·4 mm of rain in 1 h, was recorded in November 2013 in north-east Sardinia (Niedda *et al*.,

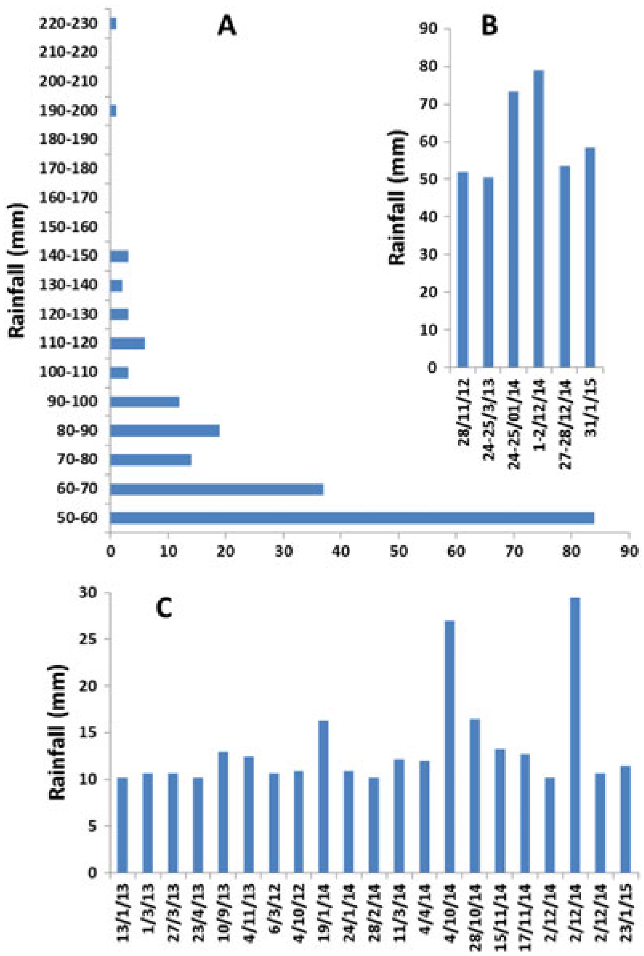

Figure 4. Days with rainfall ≥50 mm at the Montimannu station from January 1925 to April 2014 (A), dates with rainfall ≥50 mm in 24 h at the Marganai station from January 2012 to April 2015 (B) and dates with hourly rainfall ≥ 10 mm at the Marganai station for the same time period (C). [Colour figure can be viewed at wileyonlinelibrary.com]

2014). In this regard, the brushwood accumulation in strips along the maximum slope gradient would have created preferential runoff and erosion pathways.

Soil erosion had a higher negative impact at Su Caraviu, where the soils are more shallow than those at S'Isteri. Moreover, soils at Su Caraviu, due to the properties of the parent materials, are characterized by a very slow rate of soil formation (Aru *et al*., 1991). Because the upper limit of tolerable soil erosion for conditions prevalent in Europe has been set to ca. $1{\cdot}4\,\mathrm{t\,ha^{-1}\,y^{-1}}$ (Verheijen *et al*., 2009), any soil loss of more than 0·125 to $0{\cdot}304\,\mathrm{mm\,ha^{-1}\,y^{-1}}$, depending from the bulk density, should not be considered as tolerable in the studied areas. Although no aerial measurements were carried out in the present study, the visual assessment of erosion features frequently revealed, in the CWS stands, local soil mobilizations largely exceeding the tolerable rates. Anyhow, due to the lack of a dynamic ephemeral drainage network, the situation does not look to be critical at catchment level recently, as the transport and deposition processes are actually confined within the slope zone and, consequently, do not affect downslope areas. Nevertheless, in large parts of the CWS stands, the density of vegetation cover does not yet provide a satisfactory protection against the kinetic energy of raindrops, and consequently, the potential soil erosion risk is still very high.

As sustainable forest management should preferentially consider soil and promote its conservation (Kimmins, 1987), there is the necessity to adapt the CWS management to local soil, slope and climatic conditions and to adopt post-harvesting conservation procedures to minimize the negative effects of the silvicultural practices. The preservation of soil functions in managed forests requires a consideration of how forestry practices correspond to natural disturbances and natural forest soil dynamics. This is especially needed in highly sensitive and vulnerable environments, such as those with shallow soils and steep slopes in Mediterranean holm oak forests. In this regard, the simple adjustment of the final density of trees standing after the clear-cut in relation to local soil properties, slope gradient and the possibility of extreme rainfall events, a different brushwood management (e.g. accumulation in strips along the contour lines) and the restriction to the passage of wild animals would have strongly reduced the detected negative impacts on the soils of the studied areas.

CONCLUSIONS

The main short-term impacts on soil of the CWS management applied in the holm oak public forest of Marganai were the almost complete removal of organic soil horizons and the activation of soil erosion processes, mostly related to rainsplash erosion. The results emphasize the important influence of the tree forest cover on erosion and sediment mobilization in such a Mediterranean region. The soil erosion processes produced a higher negative impact at Su Caraviu, characterized by steeper slopes and shallower soils, than at S'Isteri. At present, although local soil mobilization largely exceeds the tolerable rates, the situation does not look to be critical at catchment level, but as Sardinia is regularly affected by extreme rainfall events, the potential soil erosion risk may still be considered very high. In this regard, the choice of a proper final tree density after the clear-cut, in relation to local conditions, together with a different brushwood management and the restriction to the passage of wild animals, would have strongly reduced the detected negative impacts on the soils of the studied areas.

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