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The old charcoal kiln sites in Central Italian forest landscapes

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ABSTRACT

Production of wood charcoal in the Mediterranean countries started over two millennia ago and vanished almost completely only in the last century. The legacy of this activity are thousands of abandoned charcoal kiln platforms, in which soil and vegetation characteristics are deeply affected. Understanding the consequences of such effects at the forest level demands a better knowledge of the density, distribution and morphology of these sites, as well as the influence of forest type and local geomorphological characteristics. We examined these aspects using field surveys and Airborne Laser Scanning (ALS) data in 1-ha sample quadrats distributed along an altitudinal gradient in three major forest types of Central Italy, namely evergreen sclerophyllous forest, oak-dominated thermophilous deciduous forest and montane beech forest. We found on average 5.5 kiln sites per ha. The highest overall surface proportion covered by charcoal platforms was recorded in oak-dominated forests, due to their generally larger size. In beech forests, kiln platforms were more numerous than in the other two forest types, but smaller. Density was intermediate in the sclerophyllous forests, where the overall proportion of surface was lowest. The charcoal-enriched soil layer was usually single and continuous (e.g. not interrupted by mineral layers). The thickness of this layer was similar in the three forest types, but increased with slope inclination. Several features of our kiln platforms such as density and shape were distinct from others in Central and Northern Europe, probably reflecting different forest histories and purposes for which they were built. Using ALS, we could detect all kiln platforms in beech forest on steep slopes and approximately 75% of the kilns in oak forests on hilly terrain. Hence, all further ecologically- or archaeologically-oriented study in our region at the landscape level will benefit from the use of hillshade and/or slope images from ALS data.

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1. Introduction

Based on artworks of ca. 38.000 years ago found in the caves of southern France, it appears that wood charcoal has been one of the first synthetic materials produced by man (Antal, 2003). With the beginning of iron metallurgy (Bonhôte et al., 2000; Ludemann, 2006), it then became one of the main sources of energy until the 19th century (Bonhôte et al., 2000; Fabre and Auffray, 2002; Pèlachs et al., 2009; Deforce et al., 2012; Paradis-Grenouillet, 2012; Rouaud and Allée, 2013). Its production is a very ancient form of anthropogenic forest use in the temperate regions, and was continued to satisfy the needs of the human populations in most European countries, especially for metal processing in foundries. Production of charcoal is based on the pyrolysis of wood at low temperature (from 400 °C to 600 °C) without oxygen, and was realized in special wood kilns covered by a mixture of soil and plant material (Landi and Piussi, 1988; Bonhôte et al., 2000; Ludemann, 2003; Powell, 2008; Deforce et al., 2012; Paradis-Grenouillet, 2012). In hill and mountains areas, kilns were usually prepared along footpaths in

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sites where it was possible to cut the stools in the adjacent stands and concentrate the wood in small, terrace-like platforms prepared for this purpose (Cantiani, 1955). In the Mediterranean region, various evergreen and deciduous tree species were used for charcoal production, such as oaks (*Quercus cerris, Q. pubescens* and others, except for *Q. suber*), ash (*Fraxinus ornus*), hop-hornbeam (*Ostrya carpinifolia*) and various secondary woody species that occur especially in thermophilous deciduous forests, such as *Sorbus* sp., *Acer* sp. and others (Carrari et al., 2016a). Large sclerophyllous shrubs such as the green olive trees (*Phillyrea* sp.), the strawberry tree (*Arbutus unedo*), and the heath tree (*Erica arborea*) were also used for this purpose. According to Mariotti Lippi et al. (2000), the latter species was one of the most important sources for charcoal production in S Tuscany during the Etruscan period (IV–V century b.C.).

While in most northern and central European countries the use of wood charcoal was abandoned in the 19th century due to the rapidly increasing and widespread use of coal (Deforce et al., 2012), the importance of this material in the Mediterranean area even increased during the industrial revolution, as other fuel sources were largely lacking. In Italy, its production and use mostly vanished only during the fifties, though it is still in practice today in some remote mountain areas (Landi and Piussi, 1988).

The main legacy of this traditional activity are thousands of abandoned charcoal kiln sites disseminated in present-day forests (Acovitsioti-Hameau and Hameau, 1996; Bonhôte et al., 2000; Davasse, 2000; Montanari et al., 2000; Blondel, 2006; Pèlachs et al., 2009; Paradis-Grenouiller et al., 2011). Thanks to the resistance to microbiological decomposition of charred organic material, these sites are rich in centuries-old charcoal remains (Robin et al., 2015). This provides an opportunity for the reconstruction of former woodland composition and management practices on a stand scale, using anthracological analysis and radiocarbon dating (Montanari et al., 2000; Ludemann, 2003; Ludemann et al., 2004; Nelle, 2003; Nelle et al., 2010; Pèlachs et al., 2009; Knapp et al., 2013, 2015). Other previous studies, however, showed that this practice has probably caused long-lasting ecological effects on the structure, composition and functioning of the soil and vegetation. A first important effect is the strongly increased amount of total carbon in the topsoil layers, suggesting that these sites can contribute significantly to the overall capacity of carbon stock at the forest-level (Criscuoli et al., 2014). Nutrient availability and pH are also often increased, which may lead to compositional differences in the understorey vegetation with respect to the adjacent stands (Wittig et al., 1999; Carrari et al., 2016c). In addition, the altered processes of tree recolonization in kiln sites abandoned since even decades may lead to long-lasting negative effects on forest recovery (Mikan and Abrams, 1995, 1996; Young et al., 1996; Carrari et al., 2016b).

Evaluating the magnitude of these effects and the contribution of charcoal kiln sites to the long-term carbon stock in the soil at the forest-level demands a better knowledge of their spatial distribution, density and overall surface (Schmidt et al., 2016), as well as of the characteristics of the charcoal-enriched soil layer. Previous inventory studies provided data for Germany and the Alpine area (i.e. Hesse, 2010; Ludemann, 2011; Schmidt et al., 2016), Belgium (i.e. Deforce et al., 2012; Hardy and Dufey, 2015) and Norway (i.e. Raab et al., 2015), while in S Europe most of this studies focused only on the Pyrenees (Bonhôte et al., 2000; Davasse, 2000; Pèlachs et al., 2009; Py-Saragaglia et al., 2015) and in S France (Vaschalde et al., 2008; Allée et al., 2010; Paradis-Grenouiller et al., 2011). Hence, no evidence exists for other Mediterranean regions (i.e. Italy), where factors like the frequently rough geomorphology of hilly or mountainous areas, the often heterogeneous forest environment, as well as the diversity of local traditions have probably affected the spatial distribution and the morphology of the kiln sites to a considerable extent.

Accordingly, the aims of this work were: 1) to provide a characterization of the charcoal kiln sites in the forest landscapes of a Mediterranean area (central Italy), and 2) to examine the effects of forest type and major geomorphological traits on the spatial distribution and morphology of these sites. To this purpose, we used a traditional field-based inventory and Airborne Laser Scanning (ALS) data. The latter was already successfully adopted in forest areas of C and N Europe (i.e. Ludemann, 2003; Schmidt et al., 2016), but still not in areas of S Europe. By comparing results from the field and the ALS data, it was possible to test the efficacy of the latter for kiln site detection in territories covered by oak forests with a multiple-layered structure and a massive shrub layer, or in beech forests occurring on the steep slopes of the Apennine mountain chain.

2. Regional setting

The study was performed in the forests of Tuscany (central Italy), located between 42.867017° N and 43.983427° N and 10.468035° E and 11.817308° E (Fig. 1; geographical details in Table 1).

The territory of Tuscany is characterized by three major climate and forest types, spread along an altitudinal gradient from sea level to over 1400 m: 1) meso-Mediterranean along the Tyrrhenian coast, where woodlands are mainly formed by evergreen sclerophylls and especially *Q. ilex*; 2) supra-Mediterranean on the hill systems in the central part of the region, largely covered by thermophilous mixed forests dominated by various species of deciduous oaks (mainly *Q. cerris*, *Q. pubescens, Q. petraea*); 3) montane-suboceanic on the Apennine range and Mount Amiata, where beech (*Fagus sylvatica*) and mixed beech-silver fir (*Abies alba*) forests usually occur above 900–1000 m. Mean annual rainfall and temperature in the study area vary from 650 mm and 15 °C respectively along the coast, to 1450 mm and 10.9 °C respectively on the Apennines and Mount Amiata (period 1961–1990, source: Servizio Meteorologico dell'Aeronautica Militare). The study area is characterized by a variety of geolithological formations and soil conditions, but cambisols are the prevalent soil type according to the Soil Atlas of Europe (European Soil Bureau Network, 2005).

Tuscany had an utmost importance for charcoal production because of the presence of the main Etruscan civilization. The great ability of this population in metallurgy is widely known, as well their practice to use charcoal for copper production at least since 800 b.C. (Chiarantini et al., 2009). Hence, the forests of the present study area were an inexhaustible source of all types of wood needed for the metallurgic activity since that time and they can be considered "Metallurgical Forests", as defined in Paradis-Grenouillet (2012). The activity continued, despite some fluctuations, also during the Middle age and even increased in the nineteenth century (Arrigoni et al., 1985). In later times, production of wood charcoal was such a deeply rooted practice in C Italy that it remained a major source of energy for heating and cooking, as well as for the production of high quality steel in small blast furnaces until the years 1950 and 1960 (S.I.L.T.E.M, 1946). Based on local historical documents and common knowledge, the forests investigated here have provided wood charcoal for centuries and abandoned for this purpose only about 60 years ago, as in other parts of Tuscany (Landi and Piussi, 1988; Arrigoni et al., 1985).

3. Material and methods

3.1. Selection of quadrats

For each forest type, here after indicated as "sclerophyll", "oak"

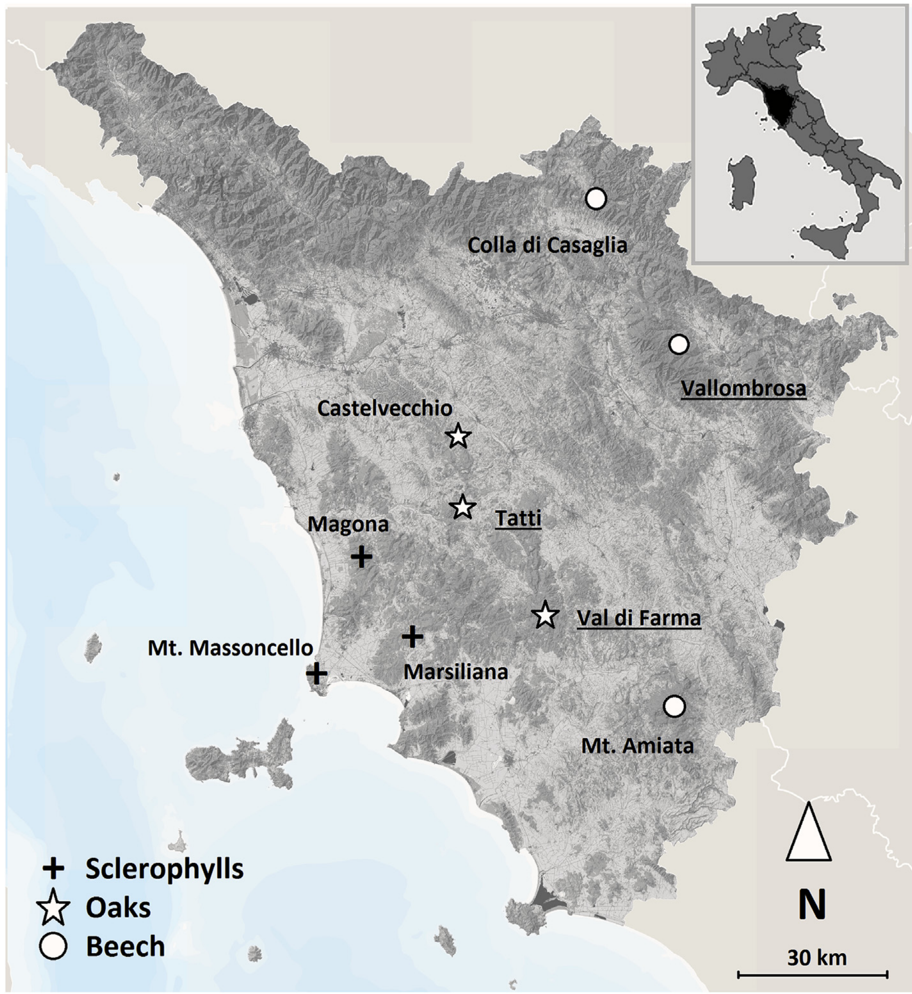

Fig. 1. Geographic location of the selected forest areas, with indication of the forest types. Areas analysed with the ALS method are underlined.

Table 1
Geographical kiln site characteristics of the forest areas. Geographical coordinates refer to the central point of the quadrats in each forest area (see Fig. 1 for their location; coordinate reference system WGS84). Forest type and density of platforms (n/ha) are given for each quadrat; altitude, slope inclination, size, thickness of the charcoal layer and preservation status of kiln sites are averaged for each quadrat.

Forest area	Latitude	Longitude	Forest type	n/ha	Altitude (m)	Slope inclination (%)	Size (m^2)	Thickness charcoal layer (cm)	Preservation status
Marsiliana	N43.04425°	E10.80938°	Sclerophylls	6	203.0 ± 7.2	5.4 ± 0.9	31.6 ± 4.3	35.3 ± 3.4	Average
Mt. Massoncello	N42.98395°	E10.49700°	Sclerophylls	6	159.0 ± 14.6	32.0 ± 11.0	31.9 ± 7.1	28.0 ± 8.7	Poor
Magona	N43.26512°	E10.63603°	Sclerophylls	4	225.3 ± 2.8	2.0 ± 2.4	24.9 ± 4.3	24.5 ± 5.2	Poor
Tatti	N43.34571°	E10.97231°	Oaks	5	465.5 ± 5.8	6.2 ± 3.2	42.2 ± 6.4	12.8 ± 1.7	Average
Val di Farma	N43.07237°	E11.28179°	Oaks	5	410.4 ± 17.4	14.0 ± 8.2	35.3 ± 5.7	29.0 ± 4.4	Good
Castelvecchio	N43.43400°	E10.99952°	Oaks	5	370.5 ± 6.0	16.3 ± 16.0	55.8 ± 14.8	21.3 ± 2.6	Good
Mt. Amiata	N42.87372°	E11.59816°	Beech	8	1405.0 ± 14.6	14.2 ± 5.8	26.8 ± 4.9	26.0 ± 7.4	Good
Colla di Casaglia	N44.05045°	E11.45977°	Beech	6	1065.3 ± 15.9	45.8 ± 36.1	33.4 ± 8.6	37.2 ± 4.4	Good
Vallombrosa	N43.433950°	E11.342388°	Beech	6	1356.8 ± 15.7	67.7 ± 16.2	22.0 ± 4.9	30.3 ± 0.5	Good

and “beech”, we selected three main representative forest areas among those described above (Fig. 1; Table 1).

To analyse the distribution and morphology of the kiln sites, we used field inventory surveys in all the nine areas (Fig. 1). In each forest areas, we first identified the part of difficult access for geomorphological reasons (e.g. slope steepness, rocky outcrops, watercourses) using 1:10.000 topographic maps. Next, we randomly selected one point in the remaining accessible zones as the centre of a sample quadrat of 1 ha. In this way, nine quadrats were defined and localized in the field with GPS devices (Table 1). For two oak areas and one beech area, the distribution of kiln platforms was repeated with the visual inspection of images generated by high-resolution ALS data.

3.2. Field inventory and data analysis

In each quadrat, all charcoal platforms were identified in the field and described using the following variables: 1) altitude; 2) slope inclination; 3) slope aspect; 3) tree and shrub species ≥4 m occurring in a circle with 15 m radius external to the perimeter of the platform; 4) preservation status (poor, average, good) based on intensity of soil erosion, impact of human activities and herbivores; 5) shape; 6) size (based on major and minor diameter) and 7) thickness of the charcoal layer detected with a soil core, easily recognizable from the mineral layer for the blackish colour and the abundance of charcoal fragments of various size (Fig. 2C).

For each forest type, we determined the average density and surface proportion of kiln platforms per hectare, and the mean thickness of the charcoal-enriched layer.

Next, the effects of forest type and slope inclination on density, size and charcoal layer thickness were tested using two model structures with different combination of variables in R 3.1.2 (R core team, 2014).

First we used a generalized linear model (using R function glm from the stats package) to test the effect of the forest type, the size and slope inclination of the kiln sites on their density per area, with a Poisson error distribution, log link (lme4; Bates et al., 2014) and parameter estimation via maximum likelihood.

Next, we tested the influence of forest type and slope inclination on kiln platform size using mixed models allowing variation between "forest areas" (random factor), in order to remove from the model the variance due to the spatial clustering of the kiln sites in each forest type. The starting model was fitted with a linear mixed model (lmer) with a Gaussian error distribution. The model selection followed the protocol of Zuur et al. (2009), where the structure yielding the lowest value for Akaike's Information Criterion (AIC; Akaike, 1973) was considered to be most consistent with the data. The same model selection was used to test the effect of forest type, kiln platform size, slope inclination and random effect of quadrats on the thickness of charcoal layer. As models contained random effects, a conditional R^2 was calculated (Nakagawa and Schielzeth, 2010; MuMIn package; Bartoń, 2013). The thickness of charcoal layer was also compared between forest types using ANOVA.

3.3. Airborne Laser Scanning

This method was applied in two quadrats of thermophilous deciduous forest (Tatti and Val di Farma) and one beech forest quadrat (Vallombrosa). Unfortunately, we could not include any of the three sclerophyllous areas since Lidar data are still lacking for most of the Tuscan territory, especially the Mediterranean parts.

In the Tatti and Val di Farma forests, ALS surveys were performed in May 2013 using an ALS50 Leica Geosystems sensor. This instrument recorded four echoes per pulse, with an average laser point density of approximately 4 laser points per m^2; the scan-angle was 60°. In the Vallombrosa forest, the ALS dataset was acquired in May 2015 with a RIEGL LMS-Q680i sensor, which recorded the full waveform with an average laser point density of approximately 5 laser points per m^2. The scan angle was 30°.

The TerraScan software was used for the preparation of the ALS datasets (Terrasolid, 2005). Standard pre-processing routines were first carried out to remove outlying pulses due to sensor errors. Then the point cloud was classified into ground and non-ground returns on the basis of the adaptive Triangulated Irregular Network (TIN) model algorithm (Axelsson, 2000). Ground returns were interpolated to generate a TIN, which was used to calculate the ground height for each ground return. A Digital Elevation Model (DEM) in grid format with a geometric resolution of 1 m was created. Finally, a slope map (in degrees) and a hillshade map were generated from DEM to visualize the micro-topography of the soil surface. All GIS operations were performed with ArcGIS 10.3.

The slope and hillshade maps allowed to identify potential charcoal kiln platforms in the quadrats of the field inventory. The visual interpretation was performed by an independent researcher (FB) who did not participate to the field inventory work and did not know the position of the platforms. Those that were identified in the field were then used as reference for evaluating the overall accuracy of the ALS-based detection method (Congalton, 1991).

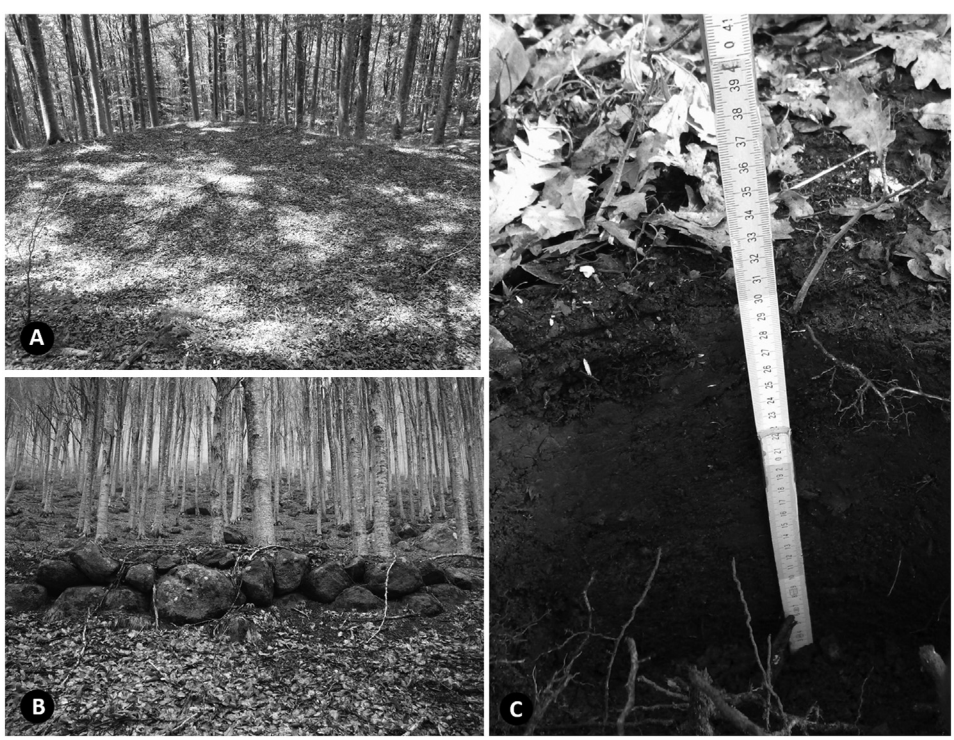

Fig. 2. Charcoal kiln platforms, showing: A) the elliptical shape and lack of forest recolonization (beech forest, Colla di Casaglia); B) old wall made with volcanic stones to sustain the platform in the beech forests on the steep slopes of Mt. Amiata; C) soil profile through the nearly 30 cm thick charcoal layer in a kiln platform in the oak-forest of Val di Farma.

4. Results

4.1. Field inventory

The altitude range of the nine quadrats was 145–230 m, 360–470 m and 1050–1420 m above sea-level for sclerophyll, oak and beech forests, respectively (Table 1). Mean slope inclination was higher for the beech forest quadrats (43%) compared to the oak (13%) and sclerophyll forests (11%), with minor differences among quadrats (Table 1). The sites on the steepest slopes were often provided with stone walls built on the downhill side to sustain the platform in a horizontal position (Fig. 2B). The platforms in the sclerophyll areas showed the poorest preservation status due to a significant level of disturbance by human activities. Those in the oak and beech forests were generally better preserved, e.g. not damaged by external disturbances.

In total, we recorded 51 more or regularly spaced kiln sites, with a minimum of 4 (Magona) and a maximum of 8 (Mt. Amiata) per quadrat (Table 1). Platforms were more numerous in the beech forest quadrats, followed by scerophylls and oaks, but differences between forest types were not significant (Fig. 3A). Results from mixed model selection also showed that size and slope inclination had apparently no effect on the number of platforms.

Platforms were always elliptical (Fig. 2A), with the shorter and longer diameter ranging from 3.8 m to 9.3 m, and 4.6 m–10.8 m, respectively. The longer diameter was always oriented along the altitudinal contour lines. The largest platforms (ca. 56 m^2) were recorded in an oak quadrat (Castelvecchio), while the smallest (ca. 22 m^2) were in a beech quadrat (Vallombrosa; Table 1). Kiln platform size was affected by forest type (Table 2), with higher values in the oak forest (on average 41 m^2) followed by sclerophyll and beech forests (30 m^2 and 27 m^2, respectively). Slope inclination had no effect on the size. The best selected model ($R^2 = 0.703$) included among-quadrats (or forest areas) variation as a random factor and explained ca. 70% of the variation (Table 2).

The total surface covered by kiln platforms in the 1 ha quadrat ranged from 100 m^2 (Magona) to 253 m^2 (Tatti). Based on mean size and density, the largest proportion of surface was found in the oak forests, where it reached 225.6 m^2, followed by beech (183.2 m^2) and sclerophylls (149.1 m^2); corresponding percentage data are shown in Fig. 3B.

The black charcoal layer containing fragments of woody charcoal was single and continuous in all sites (Fig. 2C), and its thickness ranged from 10 cm (Tatti) to 46 cm (Colla di Casaglia). Kiln platforms in the oak forests showed a thinner charcoal layer (21.6 ± 8.5 cm on average) than in the beech forest sites (28.3 ± 7.8 cm, p-value = 0.0058); an intermediate thickness was found in the sclerophyll sites (27.6 ± 8.9 cm). However, the best model structure ($R^2 = 0.412$) revealed slope inclination instead of forest type as a predictor for charcoal layer thickness. The higher the slope inclination, the thicker the charcoal layer (Table 2).

In total, 14 species of trees and shrubs ≥4 m were recorded in the forest around the kiln platforms (Fig. 4). As expected, species composition in this belt was different in the three forest types. *Quercus ilex* was the most frequent tree in the sclerophyll quadrats (27.5% on the total sites; Fig. 4), followed by *Arbutus unedo* and *Erica* sp. (mostly *E. arborea*); *Viburnum tinus*, *Phillyrea* sp. and the deciduous oak *Quercus pubescens* were present with a lower frequency. *Quercus cerris* was always present in the sites of the oak quadrats (29.4%, Fig. 4), while other dominant tree species such as *Castanea sativa, Quercus petraea, Q. ilex, Populus tremula, Ostrya carpinifolia, Arbutus unedo, Erica arborea* and *Fraxinus ornus* occurred with a frequency <10% (i.e. ca. 1/3 of kiln sites in oak forests). In the beech quadrats, kiln sites were always surrounded by *Fagus sylvatica*, while *Abies alba* was present in half of the sites (Fig. 4).

4.2. Airborne Laser Scanning data

Most of the kiln sites recorded with field surveys in the quadrats in Vallombrosa, Tatti and Val di Farma could also be detected with hillshade and slope image analysis. On the hillshade map (Fig. 5A), the platforms appeared as deviating spots in the topography, e.g. small hilly structures, sometimes with a depressed area in the centre. On slope images (Figs. 5B, 6A–C), they appeared as small, dark spots areas with a flat surface, mainly located along the altitudinal contour lines. These could be more easily distinguished on the steep slopes of the mountain area of Vallombrosa than in the hilly areas of Tatti and Val di Farma. The steeper inclination and the single-layered beech cover allowed to detect all six platforms in the Vallombrosa quadrat (overall accuracy = 100%), while the lower slope inclination and the multiple-layered oak forest cover with dense shrub layer contributed to the lower accuracy in Tatti and Val di Farma (overall accuracy = 71% and 80%, respectively). In the former area (Tatti), hillshade and slope images showed 7 sites, of which two were not actually observed in the field (and that did not exist); in the latter area (Val di Farma) the ALS-based method showed 4 sites, failing to identify one site that was clearly observed

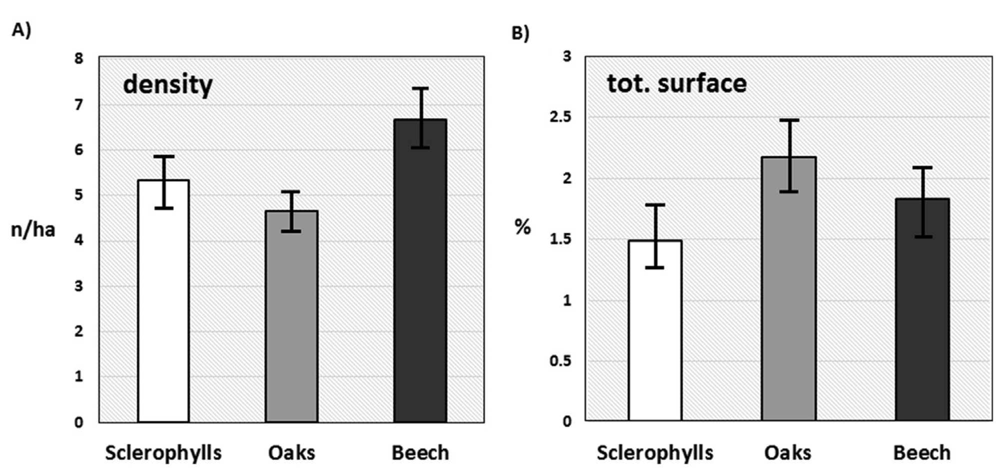

Fig. 3. A) Mean number of kiln sites per hectare in the three forest types (±confidence intervals); B) mean percentage of total surface covered by kiln platforms over the 1 ha quadrat (±confidence intervals).

Table 2
Effects of forest type and slope inclination on size and thickness of the soil charcoal layer in the kiln sites. Optimal random-effects models were selected based on AIC criteria (Zuur et al., 2009). Values for the predictor variables "slope inclination" and "forest type" (levels: oaks and beech) and are parameter estimates (±standard error) that indicate the relative change of the response variable for a unit increment in "slope inclination" or compared to the first level of the predictor variables "forest type" (level: sclerophylls) that is incorporated in the intercept. The random factor "Forest area" refers to the variation among quadrats. R^2 refers to the fraction of the variation explained by the optimal model structure; df: degrees of freedom.

Response variables	df	R^2	Intercept	Slope inclination	Forest type		Random effect
					Oaks	Beech	
Size	51	0.703	30.53 ± 4.74	/	11.80 ± 6.70	−3.64 ± 6.68	Forest area
Charcoal layer	51	0.412	24.17 ± 2.18	0.11 ± 0.05	/	/	Forest area

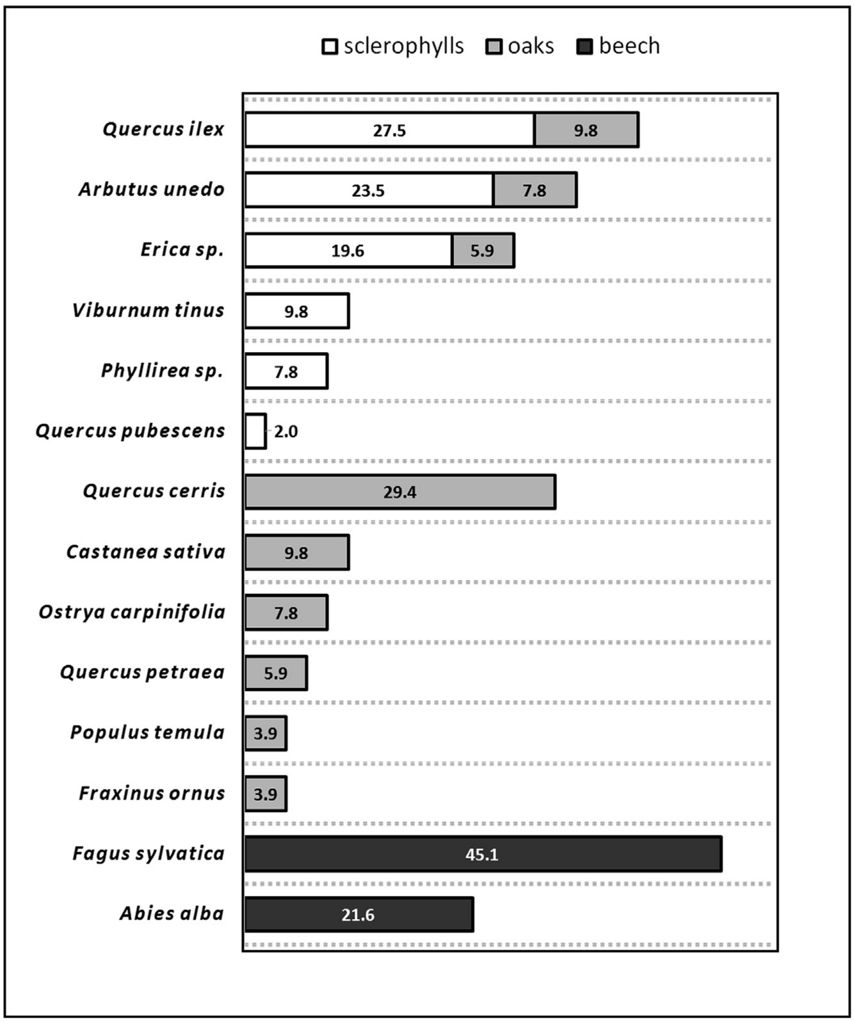

Fig. 4. Frequency (%) of the dominant woody species in the stands adjacent to the kiln sites. Percentages refer to the total number of kiln sites analysed.

in the field (Fig. 6A and B).

5. Discussion

5.1. Density and distribution of charcoal kiln platforms

The density of kiln platforms in our study area was not as high as generally indicated in previous investigations in the Mediterranean region, e. g. up to 40 sites per ha (Blondel, 2006). Davasse (2000), for example, reported a density of up to 15 sites per ha in the Barguiliere Valley of S France. Kiln density in our region, however, was considerably higher than in other forest landscapes of mainly C and N Europe. In a similar research recently conducted in Hesse (Germany), Schmidt et al. (2016) reported a frequency of one site per 7.7 ha. Around one site per ha was detected in Norway, NW Belgium, Pyrenees, and N Germany (Pèlachs et al., 2009; Deforce et al., 2012; Raab et al., 2013; Risbøl et al., 2013), while a slightly higher density was observed in the Black Forest in SW Germany (ca. 1.5/ha; Ludemann, 2010) and in the mixed broadleaf woodlands of Wallonia in S Belgium (1–3 sites/ha; Hardy and Dufey, 2015). The higher density of kilns sites in Italy and other Mediterranean areas could be associated with a more intensive forest exploitation for charcoal production, since this material has provided the energy for the everyday needs of the local populations until ca. 60 years ago

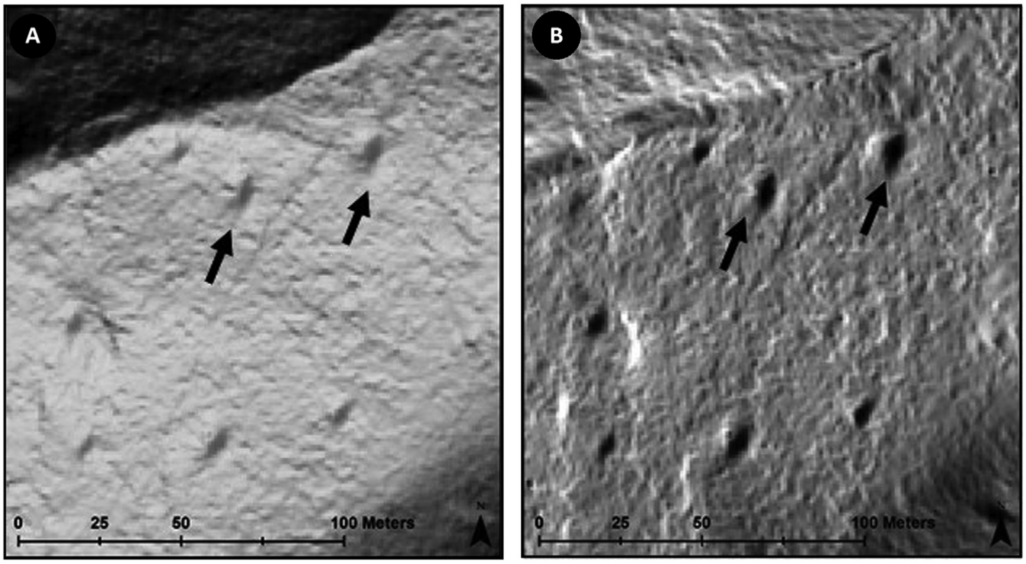

Fig. 5. Kiln platforms detected in the beech quadrat of Vallombrosa forest; close-up of (A) hillshade and (B) slope images. Arrows indicate the same two platforms in the two different image types.

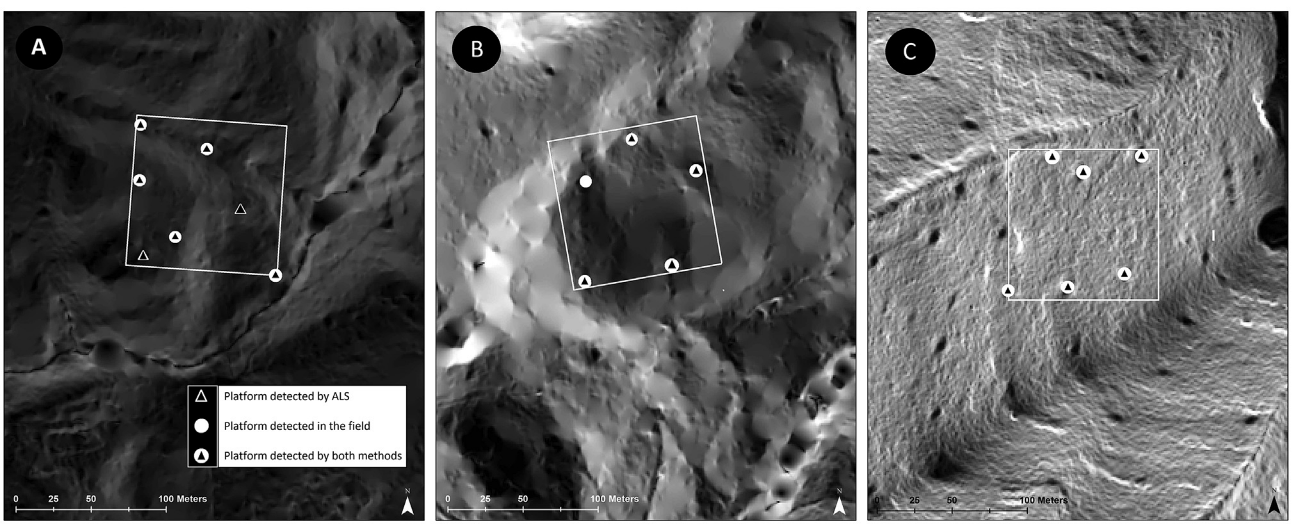

Fig. 6. Kiln platforms included in the 1-ha quadrats (squares with white borders) detected on the slope maps of the oak forest areas of A) Tatti and B) Val di Farma and beech forest area of C) Vallombrosa.

(Landi and Piussi, 1988). In addition, the practical problem of carrying away large amounts of firewood from coppice woodlands on rough terrains has led to its transformation into a much lighter material directly in the forest. Similarly to other regions, people of C Italy, especially in montane areas, preferred to spend days in the forests to produce charcoal than to bring heavy loads of firewood with mules along tracks on steep and rocky terrains (Cantiani, 1955; Landi and Piussi, 1988).

Charcoal platforms resulted relatively homogeneously distributed, similarly to other Mediterranean areas such as Mont Lozère in the region of Cévennes in France (Allée et al., 2010). In Belgium, by contrast, charcoal kilns were found to be irregularly distributed in space and time, e.g. spatially clustered and probably linked to specific but infrequent events corresponding to periods of oversupply of wood due to forest clearings (Deforce et al., 2012). On the contrary, the importance of wood charcoal for the everyday life of local people through the centuries can explain the more even spatial distribution of these sites in our region, and their apparently continuous use through time.

5.2. Shape, size and surface

While platforms were always elliptical in our region, a prevalently circular shape has been documented in Belgium and Germany (Ludemann, 2010; Deforce et al., 2012; Raab et al., 2013) and a variable shape was observed in Norway, with circular, oval, square or irregular shapes (Risbøl et al., 2013). Based on information that we obtained from the local people, the elliptical shape was adopted to facilitate collection of the charcoal from the two sides of the platform, which always extended along the altitude contour lines of the hill slope. Soil erosion on the downhill side, however, can have accentuated the elliptical shape in some cases.

The kiln sites in our study were generally smaller than in C and N Europe. On average, the platforms had a mean major diameter of

7.2 m and a minor one of 5.5 m, resulting in a mean surface of ca. 30 m^2, similarly to what observed in the Pyrenean woodlands (Bonhôte et al., 2000; Pèlachs et al., 2009). In more northern countries they ranged from 8 to 12 m in diameter, as in the Black forest (Ludemann, 2010) and in Mont Lozère (Allée et al., 2010), up to 18 m in C and N Germany (Raab et al., 2013; Knapp et al., 2015), as well as in the larch forests of the Alpine region where they measured, on average, 94 m^2 (Criscuoli et al., 2014). The larger size of the kiln platforms in the above studies may be associated, at least in part, with the different purpose for which these were prepared: in C Italy charcoal was not only addressed to iron metallurgy which required large amounts of fuel in specific periods, but it was the main source of energy for home heating and cooking, as well for many other minor uses (S.I.L.T.E.M, 1946). Hence, there was usually a more frequent need of this material, but in smaller amounts.

Model results showed that platforms were significantly larger in oak forests. This explains the higher proportion of total surface occupied by the platforms in this forest type, in spite of a lower density. In the beech forest, the total surface was lower despite a higher density of platforms, which were significantly smaller. Different reasons can exist for such effects, both indirect, i.e. associated with the geomorphology of the areas where these woodlands occur, and direct, i.e. linked to the compositional and structural characters of the forest communities. Slope inclination may be one of the factors for the indirect effects. Beech forests of central Italy occur in the mountain belt, usually above 1.000 m a.s.l. and often on steep slopes, as in our sample quadrats (on average 43% inclination). In such a condition, it was important to reduce the distance of transport of the wood material between the places where the stools were cut and the charcoal kilns. This was achieved by preparing numerous but smaller platforms mainly along the altitude contour lines. On the other hand, such a hypothesis was not supported by a significant effect of slope inclination on size and density of the kilns sites, which may indicate the role of other factors not examined in this study. These include the length of the coppicing cycle and the consequently variable amount of wood produced by the forest or the presence of other activities connected with the coal production (wood for construction, packaging etc). Direct effects could be instead associated with the different tree species composition of the forest types and their different levels of productivity. The higher biomass productivity of oak forests compared with beech and, even more, sclerophyllous forests, calculated for those areas (Castellani, 1970) may explain such difference in the proportion of kiln surface. On the other hand, anthracological studies could indicate possible changes in species composition and soil fertility of the studied forests across the centuries, and thus would be helpful to test this hypothesis.

Finally, it is noteworthy the finding of variations in the size of the platforms among areas of the same forest type which suggest differences in local forest productivity, as well as in cultural aspects. Local traditions may in fact have led to the establishment of slightly different practices in similar forest environments.

5.3. Soil charcoal layer

In all sites, the charcoal layer appeared single, continuous and rich in charcoal fragments of variable size, with an average thickness of 26 (±8.8) cm. Recent observations from a larch forest of the Italian Alps showed a thinner layer (19.3 ± 2.8 cm; Criscuoli et al., 2014), similarly to what observed in forests of C Germany (Knapp et al., 2015), while this resulted considerably thicker in the woodlands of Wallonia (ca. 35 cm on average; Hardy and Dufey, 2015). Based on oral evidence from people of villages in C Italy, the same platforms were used repeatedly at given time intervals, in correspondence with forest utilizations at the end of the coppice cycles (6–12 years i.e. S.I.L.T.E.M, 1946; Cantiani, 1955; Landi and Piussi, 1988). Such a short rotation is possibly a reason for the single, continuous and relatively thick charcoal layer. The repeated use of the sites on hill and mountain slopes is supported by the positive effect of slope inclination on the thickness of the charcoal layer. The steeper the slope on which the platform was placed, the harder was the work to build it, which often required to prepare stone walls on the downhill side to sustain the terrace in a horizontal position (Fig. 2B). Such an investment of time and energy was done in the perspective of a repeated use of the same kiln site for long periods, which probably resulted in the formation of a thicker layer than in the sites on less steep terrains. Indeed, platforms on the steeper slopes of the beech forests showed on average the thickest layer (28.3 ± 7.8 cm). Whether other factors have contributed to the formation of a single and continuous charcoal layer, such as the method adopted by the charcoal workers, should be further investigated by means of anthracological analyses.

Model results did not indicate forest type as a significant predictor for this variable mainly due to the large variation among the three sclerophyll quadrats. The six platforms of the sclerophyll quadrat in Marsiliana had a remarkably thick layer, despite the only moderately steep slopes of this area. This is possibly due to the long period of intensive exploitation of the woodlands in this southern part of Tuscany, that started as early as the Etruscan period (6th century b.C., Mariotti Lippi et al., 2000; 2002).

According to the few available studies (Carrari et al., 2016c; Criscuoli et al., 2014; Mikan and Abrams, 1995), the amount of total C contained in the soil of abandoned charcoal kiln platforms is considerably higher (generally two times) than in the soil of the adjacent forest environment. In the studies mentioned above, most of the C was in the form of carbon, whose condensed aromatic structure allows the fragments to persist in the soils over millennial time-scales (Cheng et al., 2008).

Hence, given the long-term stability of this material and the fact that it is accumulated in thick layers over a significant proportion of the forest surface (up to 2.3%), these sites will have to be considered in future estimations of the carbon stock capacity of the woodlands in our region.

5.4. Species composition

No evidence exists that local people used to make a clear selection among woody species for charcoal production, and it can be supposed that the tree species in the current stands around the platforms of all three forest types are likely the same that were used to produce the wood charcoal in former times. Lack of species selection was supported by Montanari et al. (2000) in their anthracological study on charcoal kiln sites of Liguria (NW Italy), and archaeobotanical evidence from S Tuscany proved that the forests existing during the VI-V century b.C. had the same floristic composition of the modern woods, despite their intensive exploitation for fuel production (Mariotti Lippi et al., 2000). Contrasting evidence comes from kiln sites in other parts of C and S Europe: while some showed that charcoal remains in the soil generally reflect forest composition in the surroundings, not supporting the selection of certain taxa (Ludemann, 2003, 2010; Pèlachs et al., 2009; Nelle et al., 2010), others found a low species diversity and variable composition possibly resulting from the selection of the more suitable taxa for charcoal production (i.e. Rouaud and Allée, 2013).

5.5. Application of the Airborne Laser Scanning (ALS) method

The combination of hillshade and slope images derived from ALS data emerged as a promising approach for the detection of kiln sites in the variable conditions of vegetation and terrain of our region. Using only hillshade maps, Digital Elevation Models (DEMs), or Local Relief Models as in previous studies in N and C Europe (Hesse, 2010; Ludemann, 2011; Bollandsås et al., 2012; Deforce et al., 2012; Risbøl et al., 2013) was not sufficient to identify the kiln platforms in the case of hilly or mountainous areas such as those sampled here. Overall detection accuracy was 100% in the case of the Vallombrosa beech forest, where kiln sites were unambiguously identified thanks to the lack of natural "morphological equivalents", as already observed in Germany (Hesse, 2010). Accuracy was lower in the case of the two quadrats with oak-dominated vegetation. In one of these (Val di Farma), one kiln site inventoried in the field was not detected by ALS data, while in the other one (Tatti) two sites that could not be observed in the field were detected by this method, even by varying exposition parameters. Reasons for the higher precision in the beech forest depend firstly on the higher ALS point density that was available for this area, compared with the two other quadrats. Indeed, Bollandsås et al. (2012) suggested that detection success of cultural and archaeological remains in forests increases with increasing density of points. Also, the steep slopes, the simpler (e.g. single-layered) forest structure and the lack of shrub vegetation contributed to such an elevated accuracy in this quadrat. In the two oak areas, the less inclined slopes and the structural density of the forest stands have probably limited the efficacy of this method, since more complex patterns of shadowing and texture result from more complex vegetation landscapes on irregular terrains (Amable et al., 2004). For example, some features created by the uprooting of large trees in points with low slope inclination may have caused misinterpretations (Hesse, 2010). According to Ludemann (2011), factors such as (1) bad conservation, by e.g. erosion, forest road construction, wood transport etc., (2) heterogeneities of the ground surface, or (3) vegetation with dense herb or shrub layer can reduce the reliability of the ALS method. Hence, this cannot completely replace the field-based inventories when an absolute precision is needed (Deforce et al., 2012).

6. Conclusions

This investigation allows a better knowledge and understanding of a major legacy of human activities in the forests of the Mediterranean region, and shows that some characters of the kiln sites in our study area differ from those in other parts of Europe. In the coppice woodlands of C Italy, the repeated events of wood charcoal production in the same sites have left thousands of small platforms more or less regularly spaced in the forest landscapes. As expected, geomorphological factors and forest type affected some of the characteristics of the kilns platforms but local traditions and practices could have also contributed to this differentiation.

The magnitude of the effects on the soil-vegetation system at the forest level may not be neglected, taking into account the high average density, relative total surface, and amount of charcoal in the soil. The data provided here could be the basis for further studies focusing on the contribution of the kiln sites to the carbon stock capacity of forest soils in our region, an aspect that has never been considered to date.

Further studies focusing on the ecological effects or the more historical, archaeological or anthracological aspects of the kiln sites in our region are needed and they will benefit from the use of ALS data. Using both hillshade and slope images is most useful in areas with similar geomorphology and vegetation. When a slightly lower accuracy can be accepted, ALS data will allow the inventory of the kiln platforms at large spatial scales, with various potential applications for more ecological and historical-archaeological investigations.

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