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# The selection of suitable sites for traditional charcoal production: ideas and practice in southern Switzerland

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ABSTRACT

In the valleys of the southernmost canton of Switzerland there are numerous charcoal production sites (CPS) where, in the past, charcoal burners produced wood charcoal which was mainly exported to the urban centres of Lombardy. Through a complete field survey in three study areas totaling 16.4 $km^2$, 1070 sites were mapped, inventoried and their position analyzed with respect to land surface curvature. Generally, wood carbonization was carried out far from the top of ridges, suggesting a preference for concave sites. In this paper we investigate the reasons behind this distribution pattern. Scientific literature and ethnographic accounts were reviewed to find site characteristics that charcoal burners took into consideration. We then analysed the correspondence between these written sources and evidence of charcoal production sites through a spatial analysis and an experimental approach focusing on the inventoried sites. In particular, we used a new GIS tool to extract elevation profiles from a high-resolution elevation model to calculate the impact of terrain curvature on wood transport. In agreement with the contemporary literature, we explain the higher density of CPS in proximity to the bottom of runoff channels in terms of ease of transport of wood, water availability, wind protection and soil thickness. Observed differences among the study areas may be partially explained by the inverse relationship between the density of carbonization platforms along runoff channels and the average slope of the channels. Finally, by taking into account the distribution of CPS in other regions of the world, we summarize the influence of environmental factors on the relationship between CPS and the stream network.



Before the advent of modern energy vectors such as fossil fuels and electricity, wood charcoal was by far the best fuel on the market in terms of heating value, availability, transportability and storage possibilities. There are many descriptions in ancient Greek and Roman literature of traditional production methods and the different qualities and uses of wood charcoal.[1] Numerous sources and studies confirm the importance of charcoal as fuel for metallurgical and urban centres since antiquity.[2] The existence of charcoal production sites dating back to the Roman period, or even before, has been well documented in many European regions.[3]

During the last millennium, especially between the fourteenth and eighteenth centuries, most major cities in Europe developed a

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[1] The best descriptions are those of Theophrastus, *History of Plants*, V.9.1–4 and Pliny the Elder, *Natural History*, XVI.8.23.

[2] See for instance *The Acharnians* of Aristophanes; P. Gauthier, Les ventes publiques de bois et de charbon à Délos, *Bulletin de Correspondance Hellénique* 101 (1977) 203–208; J.V. Thirgood, *Man and the Mediterranean Forest*, London, 1981; P.T. Craddock, *Early Metal Mining and Production*, Edinburgh, 1995; O. Rackham, *Ancient Woodland*, Dalbeattie, 2003.

[3] See the reference list provided in the supplementary material (Appendix A).

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0305-7488/

system for the production and transport of wood charcoal from their hinterlands to ensure fuel supply.[4] Over time, the development of cities resulted in growing demand for agricultural products and wood fuels, and in the progressive depletion and destruction of the surrounding forest resources. The bigger the city, the bigger the agricultural region around it, as well as the distance from its forest reserves. Here, wood charcoal had the advantage of better transportability with respect to fire wood, since it could be produced and efficiently transported even from the most remote areas.[5]

Important evidence of past charcoal production activities can be found today in almost all large wooded hilly areas in Europe, and even in some lowland areas.[6] Remains of charcoal production sites (hereafter referred to as CPS, see Fig. 1) are by far the most important vestiges of wood charcoal manufacturing and have densities that can be higher than a hundred sites per square kilometre.[7] For many mountainous regions in Europe, such as the Apennines, the Alps and the Pyrenees, a number of studies have focused on archaeological and pedoanthracological aspects of single selected cases with the aim of reconstructing the chronology of wood charcoal production and its effects on forest composition.[8] However, rarely have CPS been systematically studied at the regional level through a complete survey as a whole population of objects.[9] Recently, some progress has been made in the automated mapping of charcoal kiln sites from high-resolution digital elevation models (DEM). However, the effectiveness of this method has been demonstrated mostly for flat or moderately hilly regions.[10] As a result, there is little reliable geographic data on the spatial distribution of CPS and very little effort has been made to analyze and understand their distribution patterns.[11] This is surprising given that historical and ethnographic sources clearly suggest that a convenient CPS location could improve the efficiency of the work of charcoal burners considerably.[12] Moreover, the few systematic maps that are available show evidence that CPS distribution patterns differ in relation to local and regional topographic characteristics such as aspect, slope, elevation, curvature, roughness and remoteness.[13] Finally, mapping and analyzing local CPS distributions and the related organization of charcoal burning activities is becoming urgent because of the progressive disruption of abandoned CPS.[14]

In this paper we focus on 1070 charcoal production sites inventoried in three study areas in southern Switzerland that have been shown to be non-randomly distributed in terms of land surface curvature.[15] Specifically, CPS are more likely to be found close to the bottom of concave features, such as stream bed and runoff channels, and far from the top of ridges. The main objective is to discuss the reasons why charcoal burners chose these CPS and to establish to what extent the observed CPS distribution patterns can be explained by the traditional knowledge of the working methods of charcoal burners. We address the following questions. According to written historical sources, which criteria had to be taken into consideration by charcoal burners when choosing where to place CPS? Do the spatial characteristics of the inventoried CPS fit historical and ethnographic knowledge on the working methods of charcoal burners? Do the locations of the inventoried CPS offer some advantages, particularly in terms of energy needed to move

[4] F. Depelchin, *Les forêts de la France*, Tours, 1887; M.-H. Bourquin-Simonin, *L'approvisionnement de Paris en bois de la Régence à la Révolution*, Clamecy, 2006; S. Bartoletto, Città e ambiente - Dalla legna al carbon fossile: i consumi di combustibile a Napoli nel corso dell'Ottocento, *Mélanges de l'École Française de Rome. Italie et Méditerranée* 116 (2004) 705–721; J.U.B. Sanz, Combustible para Madrid en la edad moderna. El difícil equilibrio entre las necesidades urbanas y los recursos del territorio, *Mélanges de l'École Française de Rome. Italie et Méditerranée* 116 (2004) 685–704; J. Bond, Medieval charcoal-burning in England, in: J. Klápšte and P. Sommer (Eds), *Arts and Crafts in Medieval Rural Environment*, Turnhout, 2007, 277–294; L. Mocarelli, Il sistema dei navigli milanese, in: C.M. Travaglini (Ed.), *La città e il fiume: secoli XIII-XIX*, Roma, 2008, 197–208.

[5] J. Blair and N. Ramsay, *English Medieval Industries*, London, 1991; J.-P. Métailié, *Protoindustries et histoire des forêts*, Toulouse, 1992; J.A. Galloway, D. Keene and M. Murphy, Fuelling the city: production and distribution of firewood and fuel in London's region, 1290–1400, *Economic History Review* 49 (1996) 447–472; S. Cavaciocchi, *Economia e energia, secc. XIII-XVIII*, Firenze, 2003; J.A. Nieto-Sánchez, Los 'fabriqueros': una pieza clave en la organización madrileña del carbón en la primera mitad del siglo XVIII, *Revista de Historia Industrial* 44 (2010) 17–38; V. Smil, *Energy Transitions*, Santa Barbara, 2010.

[6] K. Deforce, I. Boeren, S. Adriaenssens, J. Bastiaens, L. De Keersmaeker, K. Haneca, D. Tys and K. Vandekerkhove, Selective woodland exploitation for charcoal production, *Journal of Archaeological Science* 40 (2013) 681–689; A. Raab, M. Takla, T. Raab, A. Nicolay, A. Schneider, H. Rösler, K.-U. Heußner and E. Bönisch, Pre-industrial charcoal production in Lower Lusatia, *Quaternary International* 367 (2015) 111–122.

[7] C. Dubois, J.-P. Métailié and V. Izard, Archéologie de la forêt charbonnée, in: J. Burnouf, J.-P. Bravard and G. Chouquer (Eds), *La dynamique des paysages protohistoriques, antiques, médiévaux et modernes*, Sophia Antipolis, 1997, 525–540; B. Davasse, Forêts, charbonniers et paysans dans les Pyrénées de l'Est du Moyen-âge à nos jours, unpublished PhD thesis, Université Toulouse le Mirail, 2000; T. Ludemann and O. Nelle, *Die Wälder am Schauinsland und ihre Nutzung durch Bergbau und Köhlerei*, Freiburg, 2002; S. Klemm and O. Nelle, Interdisziplinäre Untersuchungen von Kohlstätten aus Mittelalter und Neuzeit in der Eisenerzer Ramsau, Steiermark, *Archaeologia Austriaca* 89 (2005) 269–330; T. Ludemann, Airborne laser scanning of historical wood charcoal production sites, in: E. Badal, Y. Carrión, M. Macías and M. Ntinou (Eds), *Wood and Charcoal Evidence for Human and Natural History*, València, 2012, 247–252; O. Nelle, D. Jansen, K. Evers, R. Weber and M. Schwabe, Relikte der Köhlerei, in: K. Kaiser, J. Kobel, M. Küster and M. Schwabe (Eds), *Neue Beiträge zum Naturraum und zur Landschaftsgeschichte im Teilgebiet Serrahn des Müritz-Nationalparks*, Berlin, 2015, 137–147.

[8] See the reference list provided in the supplementary material (Appendix B).

[9] E.B. Rennie, *The Recessed Platforms of Argyll, Bute and Inverness*, Oxford, 1997; A. von Kortzfleisch, *Die Kunst der schwarzen Gesellen, Köhlerei im Harz*, Clausthal-Zellerfeld, 2008; A. Pèlachs, J. Nadal, J.M. Soriano, D. Molina and R. Cunill, Changes in Pyrenean woodlands as a result of the intensity of human exploitation, *Vegetation History and Archaeobotany* 18 (2009) 403–416.

[10] Ludemann, Airborne laser scanning; Raab, Takla, Raab, Nicolay, Schneider, Rösler, Heußner and Bönisch, Pre-industrial charcoal production in Lower Lusatia; G. Rassat, J.-P. Toumazet, F. Cerbelaud, R. Crouzevialle, P. Allée, N. Dieudonné-Glada and M.-C. Bal-Serin, *Le LiDAR: pour une histoire renouvelée des forêts charbonnées de plaine charentaises*, poster presentation, XX$^{e}$ colloque d'archéométrie du GMPCA, Besançon, 2015; E. Carrari, *Legacy effects of former charcoal kiln sites on the forest vegetation of a Mediterranean area*, Università degli Studi di Firenze, 2015; A. Dupin, O. Girardclos, C. Fruchart, C. Laplaige, D. Sordoillet, A. Dufraisse, L. Nuninger and É. Gauthier, *Anthracology of Charcoal Kilns in the Forest of Chailluz (France) as a Tool to Understand Franche-Comté Forestry from the 15th to the early 20th Centuries*, Anthraco2015: 6th International Anthracology Meeting, Freiburg im Breisgau, 2015; A. Schneider, M. Takla, A. Nicolay, A. Raab and T. Raab, A template-matching approach combining morphometric variables for automated mapping of charcoal kiln sites, *Archaeological Prospection* 22 (2015) 45–62.

[11] M.-L. Hillebrecht, *Die Relikte der Holzkohlewirtschaft als Indikatoren für Waldnutzung und Waldentwicklung*, Göttingen, 1982; H. Hildebrandt, B. Heuser-Hildebrandt and S. Wolters, *Kulturlandschaftsgenetische und bestandsgeschichtliche Untersuchungen anhand von Kohlholzspektren aus historischen Meilerplätzen*, Mainz, 2007; E. Carrari, E. Ampoorter, K. Verheyen, A. Coppi and F. Selvi, *Former Charcoal Kiln Sites in Mediterranean Forests, a Legacy still Affecting Vegetation Diversity and Ecology*, Anthraco2015: 6th International Anthracology Meeting, Freiburg im Breisgau, 2015; M. Schmidt, A. Mölder, E. Schönfelder, F. Engel and W. Fortmann-Valtink, Charcoal kiln sites, associated landscape attributes and historic forest conditions: DTM-based investigations in Hesse (Germany), *Forest Ecosystems* 3 (2016) 1–16.

[12] F. Denz, *Die Holzverkohlung und der Köhlereibetrieb*, Wien, 1910; F. Lugli and S. Pracchia, Modelli e finalità nello studio della produzione di carbone di legna in archeologia, *Origini* 18 (1994) 425–479; E. Weinberger, *Waldnutzung und Waldgewerbe in Altbayern*, Stuttgart, 2001.

[13] Kortzfleisch, *Köhlerei im Harz*; P. Allée, S. Paradis, F. Boumédiène and R. Rouaud, L'exploitation médiévale du plomb argentifère sur le mont Lozère, *ArchéoSciences* 34 (2010) 177–186; Ludemann, Airborne laser scanning.

[14] Our experience tells us that, in areas with rough relief and high precipitation intensities, a considerable part of the CPS may completely disappear after a hundred years.

[15] P. Krebs, M. Stocker, G.B. Pezzatti and M. Conedera, An alternative approach to transverse and profile terrain curvature, *International Journal of Geographical Information Science* 29 (2015) 643–666.

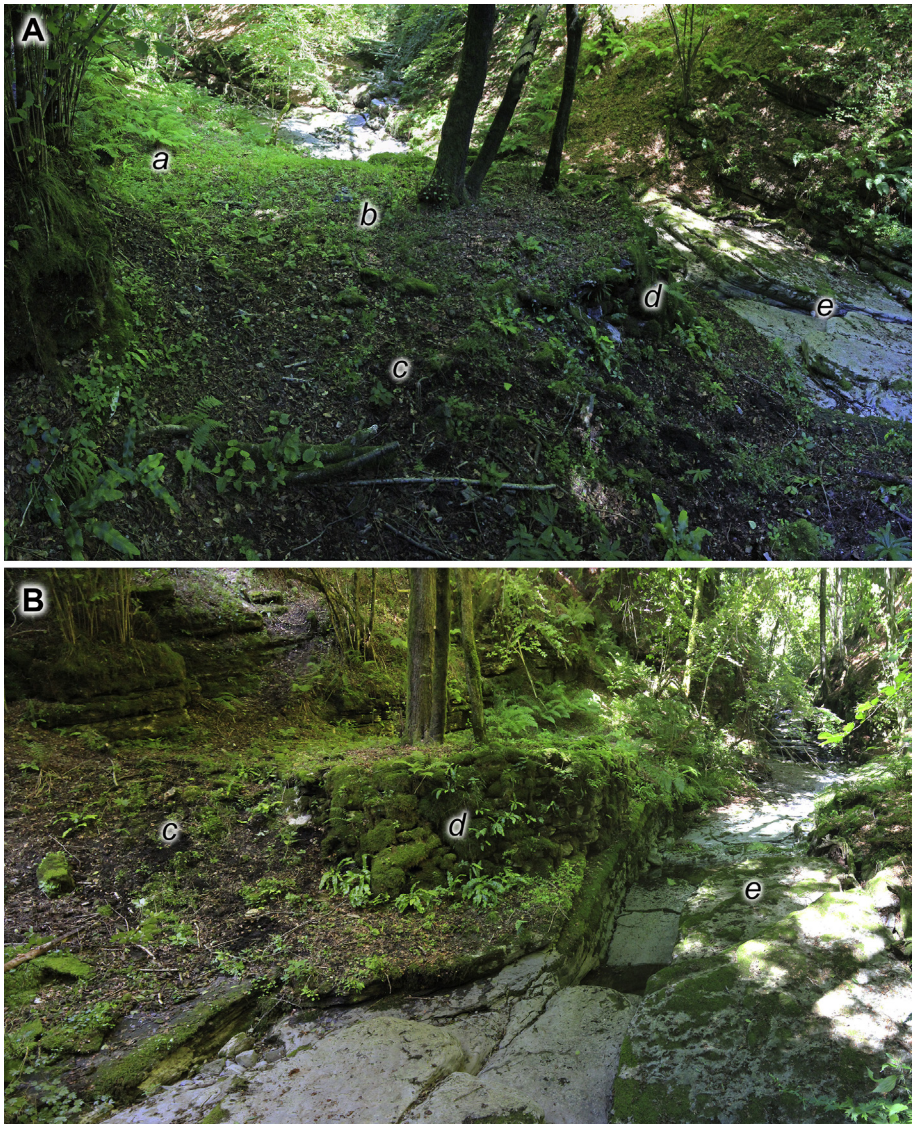


**Fig. 1.** Two pictures (A and B) of the same charcoal production site in the Muggio valley at 745 m.a.s.l.. The lowercase letters indicate the following typical structural elements: the upward excavation (*a*), the flat surface (*b*), the downward embankment (*c*) and dry-stone wall (*d*), as well as a natural drainage channel (*e*).

wood? How can the differences in CPS distribution patterns among the study areas be accounted for?

## The charcoal industry in southern Switzerland

Between the thirteenth and the sixteenth centuries northern Italy was in many respects the most developed economic area in Europe, playing a leading role in many industrial sectors.[16] Economic growth was so strong in Lombardy that by the end of the Middle Ages lowland forests were reduced to less than one tenth of the land surface and the majority of forest products had to be imported from far away.[17] As a result, the forested valleys of the upper drainage basin of the Ticino river (including the present Swiss canton of Ticino) assumed a key role as a wood reservoir for Milan, one of the largest cities in Europe. This was especially the case after the construction of the *Naviglio Grande* in the thirteenth century, a fifty kilometre navigable canal connecting the city directly to the formidable trade waterway represented by Lake Maggiore (Fig. 2).[18] In addition, and unlike other regions in Europe, the absence of significant coal deposits within Italian territory – combined with the difficulties in importing fossil charcoal – made the replacement of wood charcoal with fossil fuels very difficult. Consequently, most of the industrial revolution in northern Italy took place using traditional wood fuels so that the wood charcoal industry remained indispensable until toward the end of the nineteenth century.[19] For

[16] P. Malanima, *La fine del primato. Crisi e riconversione nell'Italia del Seicento*, Milan, 1998.

[17] E. Roveda, I boschi nella pianura lombarda del Quattrocento, *Studi storici* 30 (1989) 1013–1030; M.P. Zanaboni, Il commercio del legname e dei laterizi lungo il Naviglio Grande nella seconda metà del '400, *Nuova Rivista Storica* 80 (1996) 75–118; A. Gallus, Le importazioni di legname a Milano tra XVI e XV secolo, unpublished master's thesis, Università degli Studi di Milano, 1997.

[18] P. Mainoni, La fisionomia economica delle città lombarde, in: G. Cherubini, E. Cristiani, L. Gai, G. Petti Balbi, A.I. Pini and G. Pinto (Eds), *Le città del Mediterraneo all'apogeo dello sviluppo medievale*, Pistoia, 2003, 141–222; I. Ceschi, *Il bosco del Canton Ticino*, Locarno, 2006; F. Ogliari and A. Cremonesi, *Il Naviglio Grande*, Pavia, 2006.

[19] C. Bardini, *Senza carbone nell'eta del vapore*, Milan, 1998.

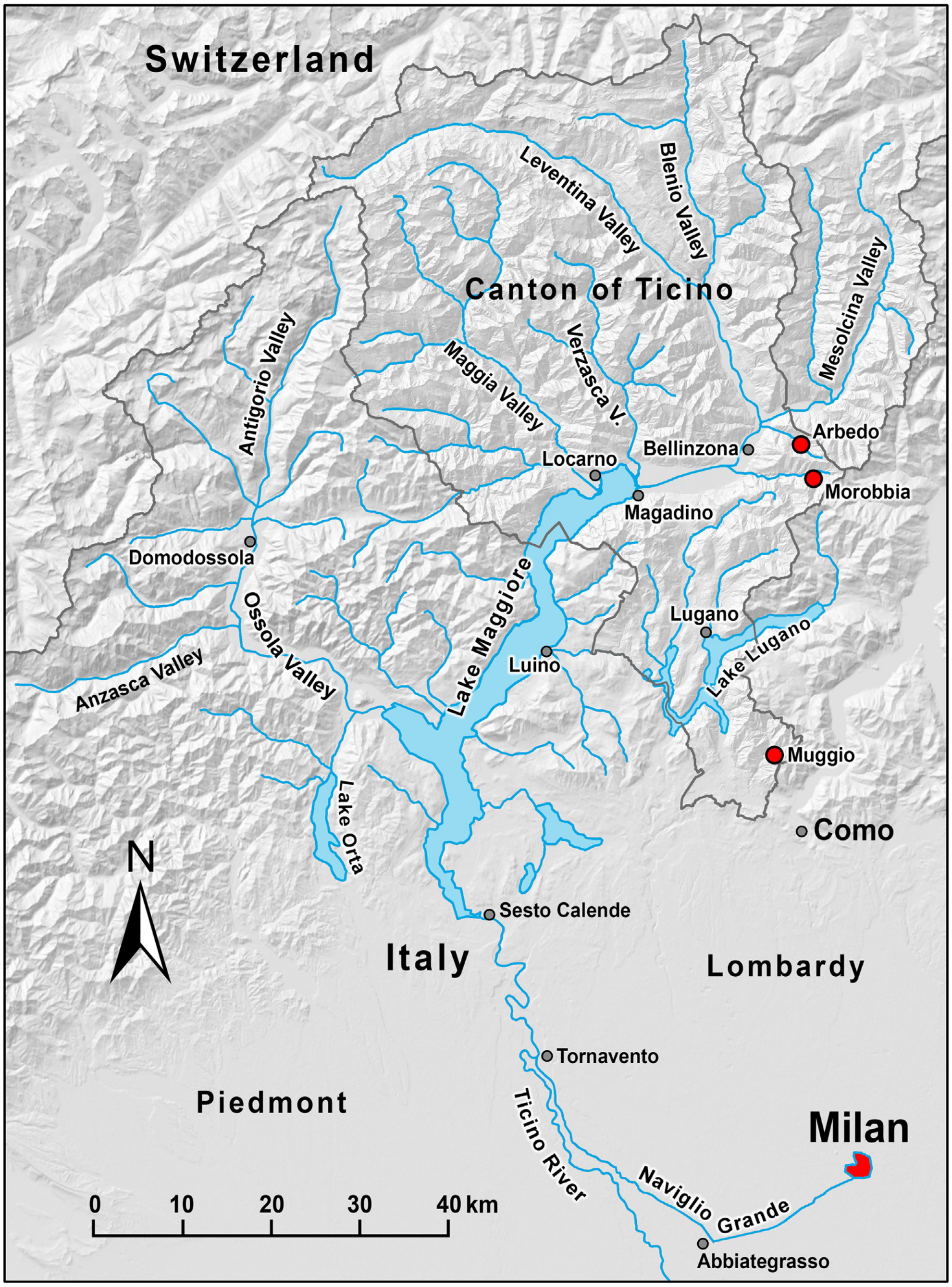


**Fig. 2.** The drainage basin of the Ticino river with Lake Maggiore and its main tributaries connected to Milan through the *Naviglio Grande* (lower right).

example, in the canton of Ticino the production of wood charcoal reached a peak of approximately ten thousand tons a year shortly after the middle of the nineteenth century, and started to decline in the last decades of the century as a consequence of the opening of the Gotthard railway tunnel in 1882.[20] As a result, in almost all valleys on the southern slope of the Alps (Piedmont, Lombardy in northern Italy and Ticino in southern Switzerland) there is considerable evidence of the past activity of charcoal burners and of CPS in particular.

## Materials and methods

In order to study the distribution of CPS we selected three areas in Canton Ticino, southern Switzerland (see Fig. 3 and Table 1). They differ in terms of geomorphological characteristics and local charcoal industry history. Arbedo was intensely exploited for wood charcoal production, especially between 1870 and 1890.[21] Morobbia was the scene of iron mining and smelting since at least the fifteenth century.[22] Muggio, which is much closer to Como and

[20] P. Krebs, Il carbone di legna dall'età della pietra all'età del barbecue, unpublished master's thesis, Université de Fribourg, 1997.

[21] Krebs, Il carbone di legna, 200–206.

[22] G. Chiesi, *Attività minerarie e siderurgiche del passato in Ticino*, Basilea, 1999, 5–11.

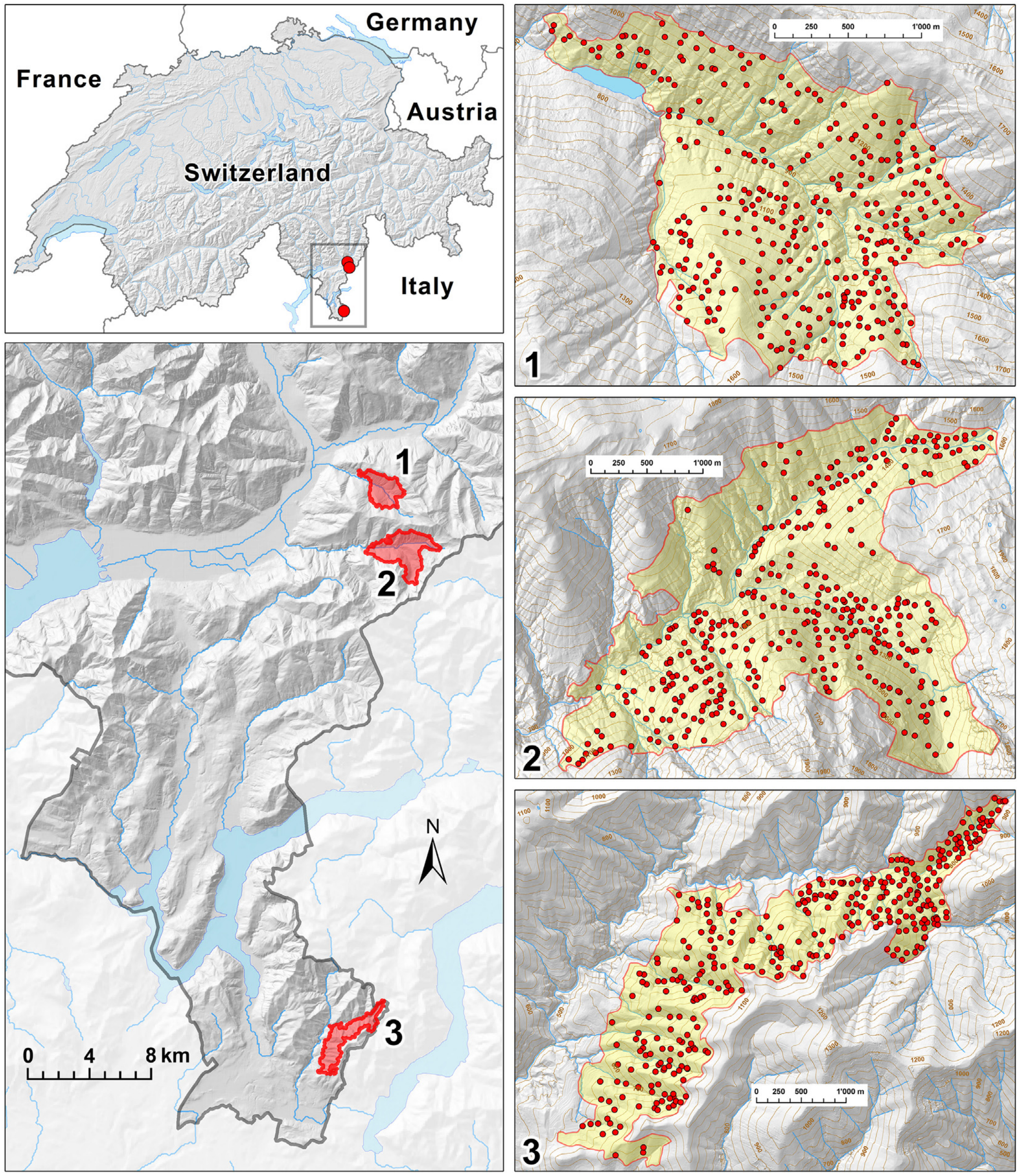


**Fig. 3.** Location of the three study areas in southern Switzerland: Arbedo (**1**), 9° 5′ 39″, 46° 11′ 54″; Morobbia (**2**), 9° 6′ 37″, 46° 9′ 43″; Muggio (**3**), 9° 3′ 9″, 45° 52′ 45″. Latitudes and longitudes refer to the centroid of the polygons. On the right a detailed map of each study area shows the distribution of the inventoried charcoal production sites.

**Table 1**
Main characteristics of the three study areas. Adapted from Krebs, Stocker, Pezzatti and Conedera, An alternative approach, 652.

| | General data | | | Altitude (m) | | | Slope (°) | | Aspect | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | No. CPS | Area (km$^2$) | Forest (%) | Min | Max | Mean | Max | Mean | North (%) | East (%) | South (%) | West (%) |
| Arbedo | 347 | 3.9 | 94.8 | 653 | 1539 | 1141.6 | 68.3 | 35.0 | 34.3 | 7.6 | 25.8 | 32.2 |
| Morobbia | 376 | 7.1 | 83.4 | 745 | 1805 | 1258.6 | 71.8 | 33.9 | 38.2 | 11.9 | 20.7 | 29.2 |
| Muggio | 347 | 5.2 | 89.7 | 538 | 1066 | 771.8 | 64.4 | 32.2 | 37.6 | 7.9 | 14.2 | 40.3 |

Milan, is probably one of the oldest areas of charcoal production within Canton Ticino.[23]

Given Ticino's general trend towards decreasing elevation, terrain roughness and average slope from north to south, the Arbedo area is the steepest, with a mean slope of 35°, and has very narrow and deeply enclosed valley floors. In the Morobbia area, the valley floors are quite wide and accessible, while the mean slope is at an intermediate value. The smoothest relief is found in Muggio, although the valley floors are narrower than in Morobbia. At present, depending on altitude and aspect, the vegetation in these

[23] P. Krebs, Prime testimonianze della protoindustria del carbone di legna nelle vallate alpine a settentrione di Milano, *Natura* 98 (2008) 109–122. According to the our first AMS measurements of $^{14}$C in wood charcoal samples, some carbonization platforms in Muggio valley were already in use in the second half of the fifteenth century (unpublished data).

study areas is dominated by sweet chestnut (*Castanea sativa*), beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*). Other common tree species are birch (*Betula pendula*), alder (*Alnus glutinosa*), maple (*Acer pseudoplatanus*), silver fir (*Abies alba*) and larch (*Larix europaea*). The forest cover is high (about 90%) and interrupted only by small pastures and occasional rural buildings in the form of small, often deserted and tumbledown settlements or isolated constructions. The road system is composed mainly of former pedestrian pathways, whereas drivable roads are rare.

A charcoal production site (CPS) is a place where the transformation of wood into charcoal through traditional methods of carbonization was achieved one or more times in the past (Fig. 1). Basically, it is an artificially flattened surface obtained through a local modification of the natural topography, resulting from a cut into the hillslope by means of a simple cut-and-fill method in which the back is dug out of the hillslope and the obtained material is used to build up the front. Depending on the slope, the height of the back excavation and of the front bank can vary considerably.[24] As a result, a CPS typically looks like a platform or small terrace which is characterized by a flat and elliptical-shaped surface with the longest diameter ranging from 4 to 20 m and an area of 20–200 $m^2$. The surface is bounded at one end by the excavation and supported at the other by an embankment or a simple dry-stone wall.[25]

Charcoal burners used the CPS as a suitable base for an earth-mound kiln where the wood carbonization process took place. The kiln is a neat pile of wood shaped as a hemisphere or a conical frustum and covered with insulating material (earth, soil and leaf litter, dry leaves, leafy branches) in order to reduce and control the oxygen intake so as to minimize combustion and maximize pyrolysis.[26] Usually, charcoal burners built the kiln site in a short timeframe, working with simple tools (shovel and pickaxe) and exploiting local materials (earth and stones).[27]

As a rule, charcoal workers preferred to reuse or repair existing CPS rather than build new ones, so that in many cases the same site was used repeatedly for the carbonization of wood with intervals of inactivity to allow forest regeneration. When the duration of abandonment is long (more than a century) and/or the site was strongly exposed to ground movement, surface runoff, erosion and other destructive processes, the CPS may have been reduced to a state of ruin, making their recognition and identification difficult.

To cope with this problem we adopted a standard field procedure to identify, locate and describe CPS. In particular, the survey consisted of systematically exploring the whole study area on foot while maintaining accuracy regardless of the difficulty and remoteness of the terrain. All evidence of CPS were analyzed in detail, regardless of their state of preservation. The field survey was supported by a high-performance GPS receiver with sub-metre accuracy (Trimble GeoXT) and detailed maps with five metre interval contour lines and two highlighted slope categories ($<20^\circ$ and $>45^\circ$) based on a high-definition DEM. For security reasons, on slopes greater than $50^\circ$, we surveyed the terrain at a distance, with the naked eye or with the help of binoculars.

Every presumed CPS encountered was further inspected for the unmistakable signs of charcoal production, such as the presence of charcoal fragments and black earth in the soil, as well as fundamental CPS structures such as embankments, dry-stone walls, flat surfaces and excavations. Each site with a sufficient number of signs to make a definitive identification of a CPS was then described in detail by recording the GPS coordinates and the site's main characteristics, such as the presence of wood-charcoal fragments in the soil, the diameter of the flat surface, the height of the dry-stone wall, the state of conservation and the vegetation cover. The field survey was conducted between April 2009 and November 2011. For safety reasons, the field team often consisted of two or three people, resulting in a total of approximately two hundred person-days of work.

The art of the charcoal burner in selecting the right places for CPS can be seen in the mediation between local constraints – especially in terms of topography, hydrology, pedology, climate, land ownership, forest composition and structure – and a heritage of traditional knowledge including different methods and strategies for maximizing the productivity of this craft industry. In order to review and summarize the best practices suggested by the literature devoted to this manufacturing activity we compiled an extensive collection of references to a wide variety of published literature on traditional methods of wood carbonization. The resulting collection consists of more than 1300 publications covering many scientific fields, including history, ethnography, forestry, economics, metallurgy, anthracology, pedology, ecology and archaeology, most of them written in western Europe during the last three centuries (Fig. 4). However, this bibliographic database also includes a wealth of other sources such as Greek and Roman literature,[28] literary works predating the Age of Enlightenment,[29] and literature referring to charcoal manufacture in other geographical contexts.[30] Owing to the composition of our database, the review is mainly related to the specific geohistorical context of western Europe during the modern/contemporary period and to its dominant charcoal production process, that is, the traditional methods of carbonization above ground through earth-mound kilns.

In approaching the analysis of CPS distribution patterns we focused primarily on the delineation of the stream network. Stream channels are among the most important topographic constraints in mountain areas and thus very likely have an influence on CPS distribution.[31] In order to provide basic data for testing this we used

[24] A. Zebedies and P. Marx, *Die Köhlerei in der Nordeifel*, Düren, 1986; Lugli and Pracchia, Modelli e finalità; Rennie, *The Recessed Platforms of Argyll, Bute and Inverness*.

[25] T. Ludemann and T. Britsch, Wald und Köhlerei im nördlichen Feldberggebiet/Südschwarzwald, *Mitteilungen des badischen Landesvereins für Naturkunde und Naturschutz* 16 (1997) 487–526; Rennie, *The Recessed Platforms of Argyll, Bute and Inverness*; T. Ludemann, H.-G. Michiels and W. Nölken, Spatial patterns of past wood exploitation, natural wood supply and growth conditions, *European Journal of Forest Research* 123 (2004) 283–292.

[26] W. Emrich, *Handbook of Charcoal Making*, Dordrecht, 1985; Schmidt, Mölder, Schönfelder, Engel and Fortmann-Valtink, Charcoal kiln sites.

[27] Bond, Medieval charcoal-burning; Kortzfleisch, *Köhlerei im Harz*; K. Menemencioglu, Traditional wood charcoal production labour in Turkish forestry, *Journal of Food, Agriculture and Environment* 11 (2013) 1136–1142.

[28] Theophrastus's *Historia Plantarum*, Cato's *De Agricultura*, Pliny's *Naturalis Historia*.

[29] V. Biringuccio, *De la pirotechnia*, Venezia, 1540; M.A. Della Fratta, *Pratica minerale*, Bologna, 1678.

[30] For Africa see for instance A.T. Ogundele, O.S. Eludoyin and O.S. Oladapo, Assessment of impacts of charcoal production on soil properties in the derived savanna, Oyo state, Nigeria, *Journal of Soil Science and Environmental Management* 2 (2011) 142–146; M. Bolognesi, A. Vrieling, F. Rembold and H. Gadain, Rapid mapping and impact estimation of illegal charcoal production in southern Somalia, *Energy for Sustainable Development* 25 (2015) 40–49. For North America see for instance R.L. Reno, Fuel for the frontier: industrial archaeology of charcoal production in the Eureka mining district, Nevada, 1869–1891, unpublished PhD thesis, University of Nevada, 1996; A. Ruby, Itinerant industry: nineteenth-century charcoal production in the Coso Mountains, *Proceedings of the Society for California Archaeology* 18 (2005) 176–180. For South America see for instance O.T. Coomes and G.J. Burt, Peasant charcoal production in the Peruvian Amazon, *Forest Ecology and Management* 140 (2001) 39–50; C.V. Rueda, G. Baldi, I. Gasparri and E.G. Jobbágy, Charcoal production in the Argentine Dry Chaco, *Energy for Sustainable Development* 27 (2015) 46–53. For East Asia see for instance S. Mimura, Charcoal burning in Japan, *Extracts from the Bulletin of the Forest Experiment Station, Meguro, Tokyo* (1915) 66–76; K. Saijo, The use of forest resources as fuel in the past in hilly areas based on the characteristics of abandoned charcoal producing kilns, *Quarterly Journal of Geography* 59 (2007) 193–204.

[31] Krebs, Stocker, Pezzatti and Conedera, An alternative approach.

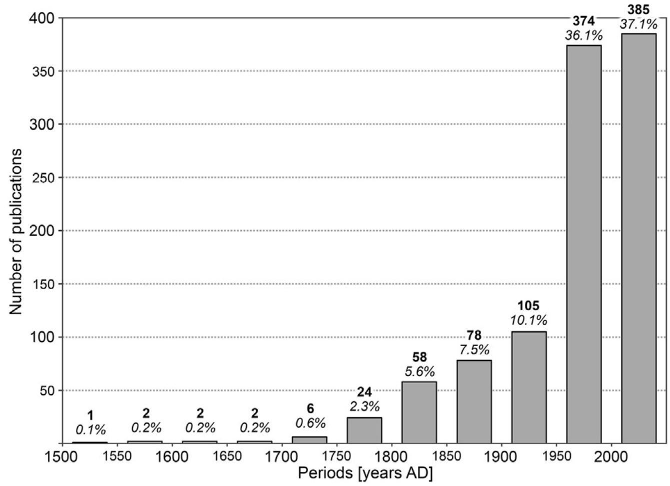


**Fig. 4.** Time distribution of the written sources collected in the literature database according to publication date (n = 1042).

common GIS procedures designed to automatically derive the stream network and other catchment characteristics from a high resolution LIDAR DEM with a pixel size of two metres.[32] As a preliminary step we created a hydrologically conditioned DEM by breaching or eliminating unnatural barriers such as forestry roads and other artifacts intercepting the water flow. We then used the Hydrology tools of the ArcGIS (ERSI©) Spatial Analyst extension to model the water flow across the DEM surface. As a result, we obtained different vector data representing the main lines of runoff concentration. We retained only the stream points that have more than 6000 $m^2$ (that is 1500 DEM cells of $2 \times 2$ m) of flow accumulation. For each stream point we then calculated the 3D distance to the nearest CPS using the Near 3D tool (in the 3D Analyst toolbox), and the average slope using the circular neighbourhood option of the Focal Statistics tool (Spatial Analyst toolbox) with radii ranging from 10 to 100 m.

With the aim of estimating the influence of topography and terrain curvature on wood transport, we used a new GIS tool to extract elevation profiles from the DEM. In a previous study we defined the Transverse Elevation Profile (TEP) as the two-dimensional cross section profile in the vertical plane oriented perpendicularly to the maximum gradient direction, and implemented a VBA (Visual Basic for Applications) macro for ArcGIS 9.3 called Elevation Profiler which was designed to automatically extract such profiles from a DEM using a point shapefile to define the centres of the profiles.[33] These elevation profiles provide a real-scale visualization of the relief of the terrain and offer multiple possibilities for analyzing the topography and the terrain curvature around spatial points. In this study we updated the Elevation Profiler GIS tool and migrated it to Visual Basic.NET (VB.NET).[34] Using this tool, we calculated TEP for all surveyed CPS, for stream points, and also for a sample of a thousand random points (RP) per study area. These were previously generated using the ArcGIS (ERSI©) function Create Random Points, forcing a minimum horizontal distance between points of 10 metres. TEP resolution was set to 1 metre (see the software description at github.com for more details).

For both CPS and RP, TEP were calculated with profile lengths ranging from 10 to 2000 metres with a 10 metre step (resulting in two hundred TEP). For channel points the TEP calculation was limited to a length of 40 metres.

In order to assess the advantages of CPS locations, if any, in terms of energy consumption for dragging the wood on the slope, we ran different types of simulations using the TEP as reference data. The basic idea behind these simulations is that the wood was usually dragged from the cutting area down to the carbonization site following, at first, the lines of runoff concentration merging together into the network of stream channels and then a transverse trackway from the axis of the channel to the destination. First, we calculated the mean energy required to move 100 kg from the two endpoints toward the centre of the profiles.[35] Second, we calculated the energy needed to drag the same mass from the TEP's lowest point toward the centre of the profile.[36] Simulations were repeated using three different coefficients of kinetic friction ($\mu_k = 0.2$, 0.3 and 0.4), three different levels of transport optimization (full exploitation of kinetic energy, exploitation reduced to one half and to one third), as well as elevation profiles of different lengths (from 10 to 2000 metres). Calculating such long TEP profiles (of more than 400 metres length) is a somewhat theoretical exercise, but is a good way to get an overview of the trends. In reality, the high density of charcoal places allows us to assume that wood transport over distances of more than 200 metres was probably rare.

The estimated energy consumption required to move an object of mass $m$ between two consecutive points along the elevation profiles can be calculated using the following three formulas:

1. $\Delta P = mg \times \Delta h$
2. $W = \mu_k \times mg \times d \cos \alpha$
3. $E = \Delta P + W$

where $\Delta P$ (in Joules) is the change in potential energy of the object with changed elevation, $m$ (kg) is the mass of the object, $g$ (9.80665 $m/s^2$) is the standard gravity, $\Delta h$ (m) is the change in elevation, $W$ (J) is the work of friction, $\mu_k$ is the coefficient of kinetic friction, $d$ (m) is the oblique distance between two points, $\alpha$ (rad) is the angle of the inclined plane, and $E$ (J) is the resulting energy consumption.

Differences between CPS and RP in terms of energy consumption were tested for all the combinations of study areas and segment lengths (10 to 2000 metres) using the Wilcoxon signed rank test. P-values are presented using the usual asterisk rating system based on the following four categories: 'n.s.' when $p > 0.05$ (not statistically significant), '*' for $p < 0.05$ (significant), '**' for $p < 0.01$, and '***' for $p < 0.001$ (highly significant).

## Approaching the geography of carbonization platforms

### *Extended review of written sources*

Nearly all texts written after the middle of the eighteenth century point out that the correct choice of the CPS is a fundamental requirement for the success and the efficiency of charcoal production work. On this basis, we were able to identify more than forty factors or conditions belonging to ten broad categories that charcoal burners were recommended to consider when choosing CPS locations (Table 2).

Some of these factors might seem contradictory at first sight, but

[32] See *swissALTI3D* in www.swisstopo.ch.
[33] Krebs, Stocker, Pezzatti and Conedera, An alternative approach.
[34] The tool – now provided as an add-on for ArcGIS version 10.0 (or higher) – is open source under GNU General Public License Version 2, and is available at github.com/Insubric/elevation-profiler.
[35] This calculation is illustrated by the green arrows in Fig. 12 (part ***b***) in the supplementary material.
[36] See the blue arrows in the Fig. 12 (part ***b***) in the supplementary material.

**Table 2**
Factors or conditions taken into consideration by charcoal burners when choosing a CPS. The full reference list of all the works cited in this table is provided in the supplementary material (Appendix C).

| | | |
|---|---|---|
| **Soil characteristics** | 1 | **Rather deep**: Svedelius 1875, 31–32; Denz 1910, 55; Olivari 2007, 19; Albisetti 2009, 197; Sibellas 2015, 96 |
| | 2 | **Rich in humus, fertile, mesotrophic, not dystrophic, ideal for the growth of forest trees**: Baudrillart 1823, 565; Denz 1910, 55; Bouchey 1969, 114; Schmidt et al 2016, 12 |
| | 3 | **Clay-rich, with few stones, little gravel and sand, not too porous and permeable to oxygen**: della Fratta 1678, 154; Massé 1769, 93; Anonymous 1773, 250; Duhamel du Monceau 1774, 659; Denz 1910, 53; Baudrillart 1823, 565; Tondi 1829, 237; Freytag 1831, 79, 82; Klein 1836, 47; Cotta 1849, 379; Svedelius 1875, 31–32; Cominotti 1884, 213; Castel y Clemente 1885, 38; Mariller 1941, 71; Correa Claver 1942, 25; Furia 1980, 24; Giordano 1986, 617; Zeier 1987, 92; Toffenetti 1993, 76; Olivari 2007, 19; Albisetti 2009, 197; Hardy & Dufey 2013, 10, 26 |
| | 4 | **Mixed, neither too sandy nor too clayey, with layers with different air permeability**: Grünberger & Däzel 1790, 265; Freytag 1831, 79; von Feistmantel 1836, 302; Klein 1836, 48; Valérius 1851, 222; Denz 1910, 55; Draghetti 1954, 155; Giordano 1986, 617 |
| | 5 | **Sand-rich, not too clayey, not too impermeable or airtight**: Roździeński 1612, 76; Freytag 1831, 79, 82; Klein 1836, 48; Alcan & Laboulaye 1845, 601; Svedelius 1875, 31; Mariller 1941, 71; Draghetti 1954, 155; Bouchey 1969, 114; Giordano 1986, 617; Izard 1992, 592; Toffenetti 1993, 76; Olivari 2007, 19; Hardy & Dufey 2013, 26 |
| | 6 | **Dry or fresh, not too moist, not swampy**: Roździeński 1612, 76; von Carlowitz 1732, 252; von Moser 1757, 376; Stahl & Stahl 1773, 573; Grünberger & Däzel 1790, 265; Baudrillart 1823, 565; Tondi 1829, 237; Freytag 1831, 80; Klein 1836, 47; Correa Claver 1942, 25; Alcan & Laboulaye 1845, 601; Valérius 1851, 222; Percy 1875, 366; Svedelius 1875, 30, 33; Castel y Clemente 1885, 38; Juhlin-Dannfelt 1923, 634; Izard 1992, 592; Schirren 2007, 236; Deforce et al 2013, 688; Schmidt et al 2016, 11 |
| | 7 | **Without turf, roots, stumps, or other combustible material**: Evelyn 1670, 192; Chambers 1728, 200; Massé 1769, 92; Anonymous 1773, 250; Svedelius 1875, 31; Mariller 1941, 71; Furia 1980, 24, 44; Toffenetti 1993, 77 |
| | 8 | **With good availability of materials needed to seal the kiln such as litterfall, leaf mould and soil**: von Berg 1860, 114, 135; Attwood 1982, 14; Schirren 2007, 236; Albisetti 2009, 197 |
| **Topography, geomorphology, and geology** | 9 | **Bedrock not too solid and not too close to the surface**: Freytag 1831, 79; Svedelius 1875, 31–32; Draghetti 1954, 155; Hardy & Dufey 2013, 10, 26; Sibellas 2015, 95 |
| | 10 | **On stable ground, with a secure foundation, not subject to erosion, ground movement, landslides, rockfalls**: Del Noce 1849, 263; Svedelius 1875, 29, 33; Juhlin-Dannfelt 1923, 634; Correa Claver 1942, 25 |
| | 11 | **Not too steep, on moderately inclined slopes, with fairly level ground**: Evelyn 1670, 192; Tondi 1829, 236; Cotta 1849, 380–381; Del Noce 1849, 263; Cominotti 1884, 213; Maillat 1942, 269, 270; SILTEM 1946, 434; Giordano 1986, 617; Zebedies & Marx 1986, 99; Toffenetti 1993, 78; Reno 1996, 264, 265; Krebs 1997, 236; Ceballos Cuerno 2001, 92; Nölken 2005, 61; Bond 2007, 281; Hardy & Dufey 2013, 10, 26; Sibellas 2015, 31, 95; Schmidt et al 2016, 12 |
| | 12 | **With enough space for added structures (huts, wood piles, shelters for charcoal)**: Svedelius 1875, 30 |
| | 13 | **In a topographic concavity or depression, close to the bottom of a valley or runnof channel**: SILTEM 1946, 435; Minucci del Rosso 1941, 55; Dubois et al 1997, 530–531; Giordano 1986, 617; Zeier 1987, 91–92; Abt 1973, 161; Krebs 1997, 237–238; Acovitsióti-Hameau 2000, 337; Olivari 2007, 19; von Kortzfleisch 2008, 96; Destaing 2012, 31; Rösler et al 2012, 174; Hardy & Dufey 2013, 26, 28, 31 |
| | 14 | **In concave breaks or smooth changes of slope, at the base of slopes**: Attwood 1982, 14; Bonhote et al 2002, 221; Rösler et al 2012, 174; Warren et al 2012, 86; Hardy & Dufey 2013, 26; Saijo & Matsubayashi 2013 |
| | 15 | **Exposed to sunlight, on a sunny slope**: Cantiani 1955, 125; Giordano 1986, 617; Minucci del Rosso 1941, 55 |
| **Relation to the other preexisting CPS** | 16 | **Better to have many sites visible from the same point of view**: Reno 1996, 265 |
| | 17 | **With the right distance between CPS, with a sufficient number of CPS**: von Moser 1757, 378; Attwood 1982, 14; Toffenetti 1993, 77; Bonhote et al 2002, 221; Albisetti 2009, 197 |
| | 18 | **Better to reuse an existing site**: della Fratta 1678, 155; von Carlowitz 1732, 252; von Moser 1757, 376; Massé 1769, 93; Anonymous 1773, 250; Duhamel du Monceau 1774, 658; Grünberger & Däzel 1790, 266; Baudrillart 1823, 565; Dumas 1829, 484; Tondi 1829, 237; von Berg 1830, 103; Mugnaini 1831, 69; Klein 1836, 48; Cotta 1849, 379; Svedelius 1875, 30; Cominotti 1884, 213; Castel y Clemente 1885, 39; Juhlin-Dannfelt 1923, 634; Mariller 1941, 71–72; Minucci del Rosso 1941, 57; Correa Claver 1942, 25; SILTEM 1946, 434; Draghetti 1954, 155, 158; Cantiani 1955, 125; Bouchey 1969, 114; Giordano 1986, 617; D'Onofrio 1988, 292; Izard 1992, 592; Toffenetti 1993, 76; Parolini 1995, 45; Krebs 1997, 14; Acovitsióti-Hameau 2000, 335; Ceballos Cuerno 2001, 92; Bond 2007, 286; Olivari 2007, 19; Rösler et al 2012, 174 |
| | 19 | **Wait many days until ground cools down, or take advantage of this residual heat to increase efficiency**: von Moser 1757, 377; Toffenetti 1993, 77 |
| | 20 | **Without too much tar and resin resulting from previous carbonizations, after many uses the soil needs to be ploughed, lightened and renewed**: von Moser 1757, 377; Svedelius 1875, 32; Draghetti 1954, 158; Toffenetti 1993, 77 |
| **Fire safety, forest regeneration and protection** | 21 | **Far from buildings, villages, wood piles**: Anonymous 1773, 250; Klein 1836, 47; Naso 1987, 23; Burri 2009, 1 |
| | 22 | **Far from big trees, thick woods, scrub, dry grass**: von Moser 1757, 378; Massé 1769, 92; Anonymous 1773, 250; Duhamel du Monceau 1774, 659; Correa Claver 1942, 25; Courau 2006, 17 |
| | 23 | **Outside forests, on forest edges, in glades in the forest**: Grünberger & Däzel 1790, 265; Baudrillart 1823, 565; Klein 1836, 47; Landolt 1864, 141; Brini 1882, 328; Berruti 2001, 120; Prodon 1983, 67; Toffenetti 1993, 78; Courau 2006, 17 |
| | 24 | **Outside protected forests**: Krebs 1997, 243; Bertogliati 2014, 104-105 |
| **Water** | 25 | **Close to water**: von Moser 1757, 375; Grünberger & Däzel 1790, 265; Baudrillart 1823, 565; Tondi 1829, 236; von Berg 1830, 102; Freytag 1831, 78, 81; von Feistmantel 1836, 302; Klein 1836, 47; Alcan & Laboulaye 1845, 601; Del Noce 1849, 263; Valérius 1851, 222; Percy 1875, 366; Svedelius 1875, 30; Brini 1882, 328; Juhlin-Dannfelt 1923, 634; SILTEM 1946, 435; Draghetti 1954, 155; Cantiani 1955, 125; Düsterloh 1967, 71; Attwood 1982, 14; Giordano 1986, 617; Zebedies & Marx 1986, 70–71; Parolini 1995, 45; Ceballos Cuerno 2001, 93; Nölken 2005, 62–63; Bond 2007, 281; Olivari 2007, 19; Schirren 2007, 236; Euba Rementeria 2008, 52; von Kortzfleisch 2008, 96; Albisetti 2009, 197; Burri 2009, 1; Rösler et al 2012, 175; Deforce et al 2013, 688; Samojlik et al 2013, 4 |
| | 26 | **Protected against runoff, stagnation and flooding**: Massé 1769, 92; Anonymous 1773, 250; Stahl & Stahl 1773, 573; Duhamel du Monceau 1774, 658; Grünberger & Däzel 1790, 265; Baudrillart 1823, 565; Freytag 1831, 78; Mugnaini 1831, 69; von Feistmantel 1836, 302; Klein 1836, 47; Valérius 1851, 222; von Berg 1860, 114; Svedelius 1875, 30, 32 |
| **Wind** | 27 | **Protected against wind and storm, free from drafts**: Evelyn 1670, 193; Chambers 1728, 200; von Moser 1757, 378; Duhamel du Monceau 1774, 669; Grünberger & Däzel 1790, 265; Baudrillart 1823, 56; Juhlin-Dannfelt 1923, 634; Dumas 1829, 487; Tondi 1829, 237; von Berg 1830, 102; Freytag 1831, 78, 80; Mugnaini 1831, 69; von Feistmantel 1836, 302; Klein 1836, 47; Alcan & Laboulaye 1845, 601; Cotta 1849, 379; Del Noce 1849, 263; Valérius 1851, 222; Percy 1875, 366; Svedelius 1875, 29; Brini 1882, 328; Cominotti 1884, 213; Castel y Clemente 1885, 38; Mariller 1941, 71; Minucci del Rosso 1941, 55; SILTEM 1946, 434; Draghetti 1954, 155; Cantiani 1955, 125; Bouchey 1969, 120; Giordano 1986, 617; Zebedies & Marx 1986, 97; Prodon 1983, 70; Izard 1992, 592; Toffenetti 1993, 76; Parolini 1995, 45; Acovitsióti-Hameau 2000, 335; Ceballos Cuerno 2001, 93; Bond 2007, 281; Olivari 2007, 19; Albisetti 2009, 197; Burri 2009, 1; Rösler et al 2012, 174 |

**Table 2** (*continued* )

| | |
|---|---|
| **Wood and forest** | 28 **Large supply of wood and forest reserves**: Baudrillart 1823, 565; Svedelius 1875, 30; Reno 1996, 266–269; Krebs 1997, 236; von Kortzfleisch 2008, 96; Nölken & Ludemann 2015, 95 |
| | 29 **Close to wood reserves, ease of transport**: Biringuccio 1540, 62; von Carlowitz 1732, 252; von Moser 1757, 375; Massé 1769, 93; Anonymous 1773, 250; Stahl & Stahl 1773, 573; Duhamel du Monceau 1774, 658; Grünberger & Däzel 1790, 265; Baudrillart 1823, 565; Tondi 1829, 236; von Berg 1830, 102; Freytag 1831, 78; Klein 1836, 47; Alcan & Laboulaye 1845, 601; Cotta 1849, 379; Valérius 1851, 222; Svedelius 1875, 30; Castel y Clemente 1885, 38; Denz 1910, 205; Draghetti 1954, 155; Düsterloh 1967, 71; Giordano 1986, 617; Zebedies & Marx 1986, 93; Monesma Moliner 1993, 63; Toffenetti 1993, 76; Reno 1996, 265; Ludemann & Britsch 1997, 518; Ceballos Cuerno 2001, 93; Bonhote et al 2002, 221; Abry et al 2005, 283; Baucells Mesa et al 2006, 533; Small & Stoertz 2006, 76; Bond 2007, 281, 290; Goepp et al 2007, 349; Schirren 2007, 236; Euba Rementeria 2008, 52; von Kortzfleisch 2008, 96; Burri 2009, 1; Destaing 2012, 31; Saijo & Matsubayashi 2013; Sibellas 2015, 96 |
| | 30 **Age of forest, optimal rotation age and tree trunk diameter, give preference to coppiced woodland**: Cominotti 1884, 212; Minucci del Rosso 1941, 54, 55; Maillat 1942, 270, 275; Draghetti 1954, 158; Lugli & Pracchia 1994, 459; Abry et al 2005, 283; Paradis Grenouillet 2012, 134 |
| | 31 **Tree species composition**: Villa & Villa 1847, 53; Maillat 1942, 268, 269; Lugli & Pracchia 1994, 433, 459; Izard 2005, 270, 273; Paradis Grenouillet 2012, 133; Schmidt et al 2016, 13 |
| | 32 **Wood of good quality, with few wood knots, easy to split**: della Fratta 1678, 153 |
| | 33 **Low-quality wood, branchwood or logging slash unsuitable for timber production**: Eckert 1846, 215; Caimi 1847, 39; Landolt 1864, 136-137 |
| | 34 **Ownership and area of land lots, distinction between common and private property forest resources**: Naso 1987, 14; Krebs 1997, 243; Berruti 2001, 63, 69; Rouaud 2014, 180–181; Raab et al 2015, 118 |
| **Proximity** | 35 **Easy to load up and carry away towards collection center**: Baudrillart 1823, 565; Tondi 1829, 236; von Berg 1830, 102; Klein 1836, 47; Alcan & Laboulaye 1845, 601; Cotta 1849, 379; Valérius 1851, 222; Svedelius 1875, 30; Brini 1882, 328; Cominotti 1884, 213; Giordano 1986, 617; Abry et al 2005, 282; Burri 2009, 1 |
| | 36 **Close to paths or streets**: von Moser 1757, 375; Baudrillart 1823, 565; von Feistmantel 1836, 301; Svedelius 1875, 30; Mariller 1941, 71; Maillat 1942, 270, 273; Giordano 1986, 617; Krebs 1997, 238–241; Toffenetti 1993, 76; Acovitsióti-Hameau 2000, 335, 337; Ceballos Cuerno 2001, 92; Abry et al 2005, 282; von Kortzfleisch 2008, 96; Burri 2009, 1; Destaing 2012, 31; Manga et al 2012, 125; Deforce et al 2013, 688; Hardy & Dufey 2013, 26 |
| | 37 **Connected to metal mining, smelting industry and iron-working sites**: Small & Stoertz 2006, 76; Berge 2009, 118; Pèlachs et al 2009, 413; Raab et al 2015, 121 |
| | 38 **Not too far from charcoal burner's house**: Attwood 1982, 14 |
| **Remoteness** | 39 **In extremely remote and poorly accessible zones where timber hauling is too expensive**: Schinz 1786, 253; Caimi 1847, 39; Landolt 1864, 136–137; Maillat 1942, 266; Bogge 1987, 130; Occhi 2006, 53; Schmidt et al 2016, 12 |
| | 40 **Far from villages (for social reasons)**: Goepp et al 2007, 349 |
| | 41 **In hidden places to avoid detection (e.g. at home in the back garden)**: Bechmann 1984, 178; Baucells Mesa et al 2006, 532 |
| **Other** | 42 **On forest edge to enlarge pasture**: Goepp et al 2007, 349 |
| | 43 **Outside the pastures grazed by livestock**: Acovitsióti-Hameau 2000, 335 |
| | 44 **Along administrative boundaries to take advantage of the lack of control**: Caimi 1847, 39; Adami 1927, 309 |
| | 45 **Charcoal burners act in different ways because of their cultural background or ethnicity**: Lugli & Pracchia 1994, 459; Abry et al 2005, 284 |
| | 46 **Benefit from long tradition of charcoal burning and exploit the availability of specialized labor force**: Maillat 1942, 269 |
| | 47 **Avoid coal outcrops**: Bond 2007, 281 |

this is due to the complexity of the theme, the large numbers of written sources and the extent of the spatio-temporal domain considered. For instance, the ideal soil characteristics are described in many different ways. Some authors give preference to clay-rich soils (factor 3), while others emphasize the benefit of sand-rich soils (factor 5). On the other hand, many sources point out that CPS have to be close enough to human infrastructure (factors 35–38), while others highlight the importance of remoteness (factors 39–41). In fact it is well known that the difficulties of transport in remote forest areas could act as an important incentive for wood carbonization.[37] In this sense, the ability to find a balance between conflicting interests was probably an important aspect of the art of charcoal burning. Exceptionally, we found different sources giving diametrically opposed interpretations of the same condition (see factor 19).

Obviously, not all factors have the same rate of recurrence in the literature and the same impact in practice. The four most frequently mentioned criteria are protection against the wind (factor 27 with 42 occurrences); proximity to wood reserves and the effectiveness of wood transport (factor 29 with 41 occurrences); the convenience of reusing preexisting CPS (factor 18 with 36 occurrences) and the proximity to water sources (factor 25 with 35 occurrences). The energy consumption simulations (see below) show that factor 29 has certainly been influential in determining the spatial distribution of the inventoried CPS and the higher density of carbonization platforms along runoff channels in particular.

*Distribution patterns*

In total, 1070 CPS (347 in Arbedo, 376 in Morobbia and 347 in Muggio) were inventoried in an area of 16.3 $km^2$. This represents a remarkably high CPS density that ranges from 50 to 100 sites per square kilometre. Specifically, the average density is 88.5/$km^2$ in Arbedo, 52.7/$km^2$ in Morobbia and 66.5/$km^2$ in Muggio. As Fig. 5 shows, the average distance from the nearest CPS is 61.9 m in Arbedo $[27.6, 106.2]_{90\%}$, 71.1 m in Morobbia $[25.9, 131.7]_{90\%}$ and 69.1 m in Muggio $[21.7, 141.8]_{90\%}$, while the average area of the Thiessen polygons around CPS is 1.13 ha in Arbedo $[0.41, 2.47]_{90\%}$, 1.88 ha in Morobbia $[0.46, 5.02]_{90\%}$ and 1.50 ha in Muggio $[0.39, 4.38]_{90\%}$.

From a geospatial point of view, the inventoried CPS present significant patterns. As a general rule, CPS tend to concentrate near the stream network. However, taking a closer look, there is a clear relationship between the average slope of a stream channel (measured inside the depression in a close neighborhood around the channel bed) and the 3D distance from the nearest CPS (Fig. 6). When run-off channels and valleys are gorge-shaped and with steep slopes, CPS tend to be more distant from their beds. Specifically, the lowest values in terms of average 3D distance from the nearest CPS (less than 50 metres) are observed for stream channels

[37] T. Ludemann, Large-scale reconstruction of ancient forest vegetation by anthracology – a contribution from the Black Forest, *Phytocoenologia* 33 (2003) 664.

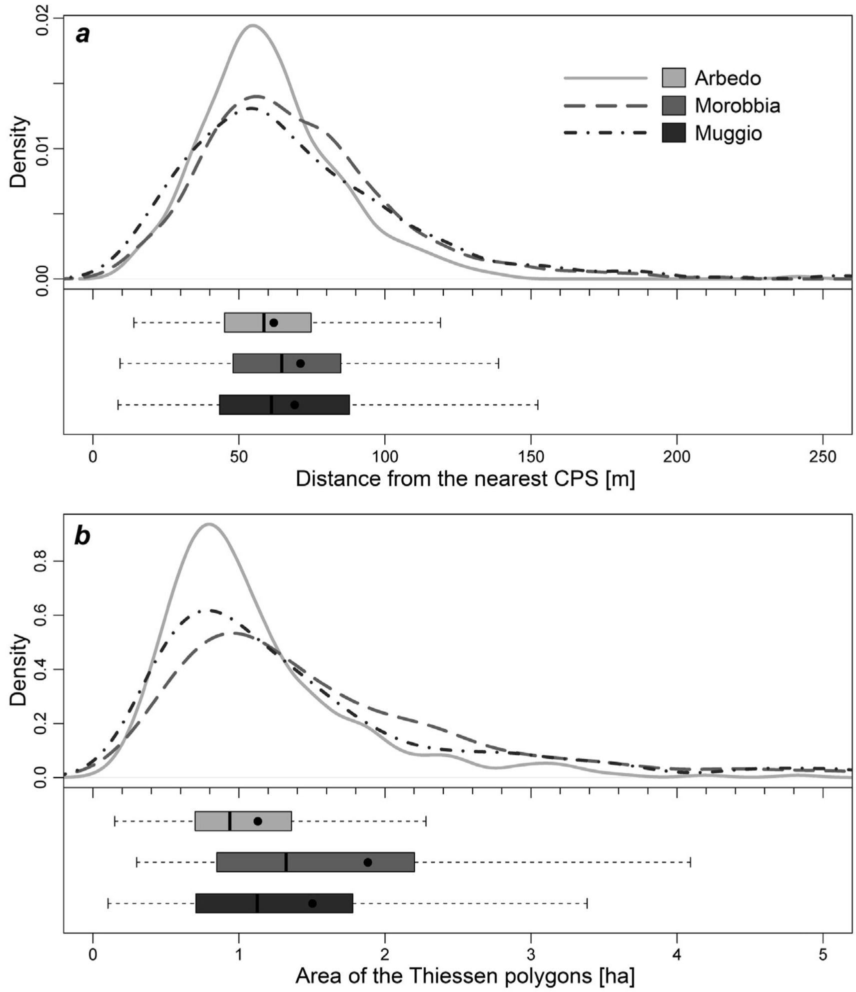


**Fig. 5.** Kernel density estimates and box-plots describing the distance between CPS (**a**) and the area of influence around CPS (**b**) in the three study areas.

with an average slope of 26–29° (circular focal statistics with 7 DEM cells of 6 × 6 metres as radius, see Table 3). This relationship is also supported by the analysis of the transverse elevation profiles of the stream channels (Fig. 7). In fact, stream points that are in the immediate vicinity of CPS have a gentler topographic profile, whereas stream points located far from CPS are generally surrounded by steep slopes.

*Simulated energy consumption for mass transport*

The simulations of the energy required to drag a mass towards the centre of the TEP show that, in general, CPS are advantageous with respect to random points. This gain varies considerably, however, primarily depending on the study area considered. The difference between CPS and RP is highly significant in Muggio and just significant in Morobbia, while in Arbedo the differences are significant only for profiles shorter than 100 metres (Figs. 8–11). Secondly, the significance of our results varies depending on the spatial scale (profile segment length) considered, although differences were always statistically significant at least within the most represented distances among CPS (40–90 metres, Fig. 5a).

It should be noted that the parameters used for energy consumption calculations may influence the results. Indeed, the reduction of energy consumption offered by CPS becomes even more evident when using a low coefficient of kinetic friction ($\mu_k$=0.2) and assuming perfect transport optimization. In these conditions, the maximal reduction of energy consumption can be observed by plotting the mean energy required to drag an object from the two ends towards the centre of the TEP (Figs. 8 and 9). The reduction is often greater than −30% in the Morobbia and Muggio valleys, with a peak of more than −50%. Instead, using a higher coefficient of kinetic friction and supposing a lower exploitation of kinetic energy, the maximum reduction of energy consumption is observed by taking the mean energy required to drag an object from the lowest point of the TEP towards its centre (Figs. 10 and 11).

*Comparing field data and written sources*

In a previous study we found that the concentration of CPS is higher in proximity to transverse and longitudinal concave features, such as runoff channels and slope breaks, coming to the conclusion that charcoal burners preferred to carbonize the wood at concave places.[38] The energy consumption simulations for mass transport conducted in this study shed light on the causes behind this spatial pattern by clearly indicating that CPS offer advantages for wood transport compared with random points. This and other key principles for interpreting the observed distribution of CPS can

[38] Krebs, Stocker, Pezzatti and Conedera, An alternative approach.

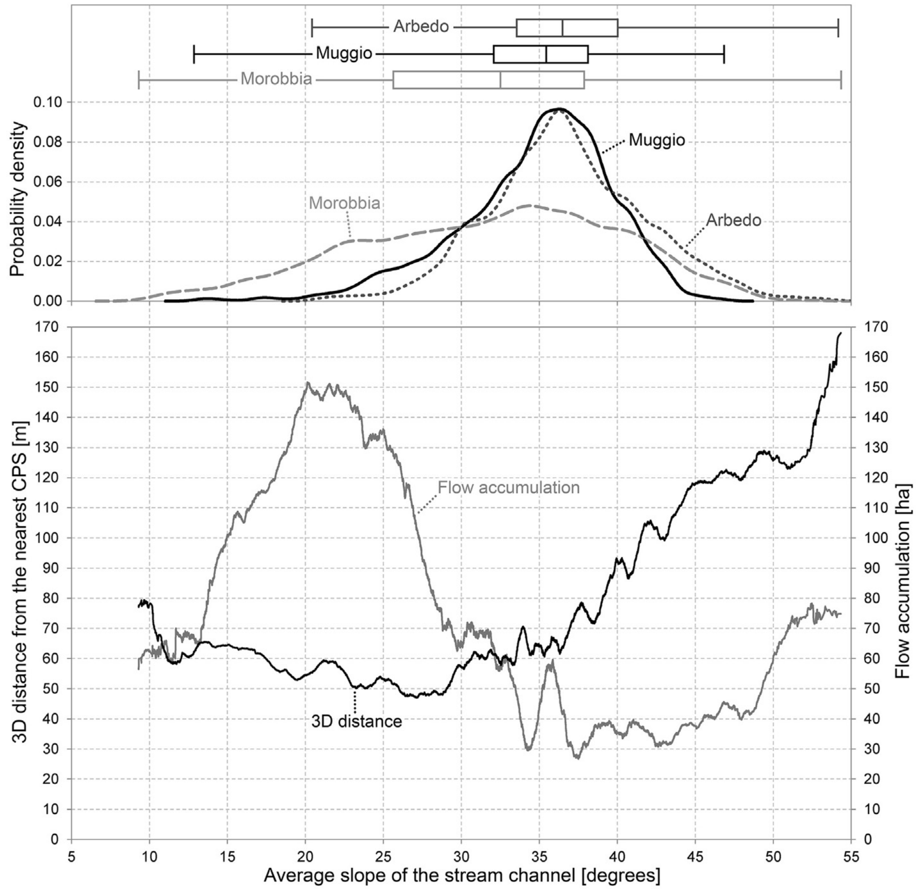


**Fig. 6.** The relationship between the average slope of the stream channel [degrees], the 3D distance from the nearest CPS [m], and the flow accumulation [ha]. Calculations were done for the stream network in the three study areas, and in particular for the 64596 stream points with more than 6000 $m^2$ (1500 DEM cells of 2 × 2 m) in terms of flow accumulation. The average slope for every stream point was calculated using circular focal statistics with a radius of 42 m (7 DEM cells of 6 × 6 m). Both curves were smoothed through a moving average (interval = 1000).

**Table 3**
Relationship between stream channel slope and distance to CPS. The data are extracted from Fig. 6.

| Average 3D distance from the nearest CPS [m] | Average slope of the stream channel [°] |
|---|---|
| >100 | >41.5 |
| >80 | >39.1 |
| <60 | 17.5–30.7 |
| <50 | 26.0–29.1 |

be found by looking closely at the best practices described in written sources. When reviewing the factors that may have influenced the selection of CPS locations (see Table 2), several major reasons arise why concave sites may be advantageous.

The ease of supply and transport of wood from the felling location to the CPS is certainly a prominent advantage (see factors 28 and 29 in Table 2). As reported in a book published in Venice in 1540, CPS must be convenient for the transport of wood.[39] And according to Carlowitz's eighteenth-century account, CPS had to be prepared in convenient and 'comfortable places' especially to facilitate the supply of wood.[40] Some authors consider the high density of CPS in itself as evidence of the great importance attached by charcoal burners to the proximity to wood reserves.[41] In mountainous regions, historical and ethnographic evidence demonstrates that, before the advent of cableways, firewood was usually conveyed to the carbonization sites by letting the logs and branches slide down by gravity or dragging them down by human power.[42] In both cases, the load of wood tended to follow the steepest descent direction and the natural drainage channels. Therefore, CPS were often located near the channels that served as conveyor tracks or transportation routes for the wood.[43]

Another advantage of concave sites is the proximity to water (see factor 25 in Table 2). In fact, good water availability was useful

[39] See 'un luogo commodo alle legna' in Biringuccio, *De la pirotechnia*, 62.

[40] See 'bequeme Oerter' in H.C. von Carlowitz, *Sylvicultura oeconomica, oder hauswirthliche Nachricht und naturmässige Anweisung zur wilden Baum-Zucht*, Leipzig, 1732, 252.

[41] See for instance 'der hohen Dichte der Meilerplätze' in Ludemann and Britsch, Wald und Köhlerei, 518.

[42] See E. Garnier, 'The coveted tree': the industrial threat to the Vosges forest in the 16th and 18th centuries, in: M. Agnoletti and S. Anderson (Eds), *Forest History: International Studies on Socio-Economic and Forest Ecosystem Change*, Wallingford, 2000, 43.

[43] See M. Landi and P. Piussi, *Il lavoro nei boschi: boscaioli e carbonai a Luco di Grezzano tra il 1930 e il 1950*, Firenze, 1988, 40; Dubois, Métailié and Izard, Archéologie de la forêt charbonnée, 530–531; Davasse, Forêts, charbonniers et paysans, 202; J. Bonhote, B. Davasse, C. Dubois, V. Isard and J.-P. Métailié, Charcoal kilns and environmental history in the Eastern Pyrenees, in: S. Thiébault (Ed.), *Charcoal Analysis. Methodological Approaches, Palaeoecological Results and Wood Uses*, Oxford, 2002, 221; N. Abry, A. Carminati, M. Centini, P. Hanus, C. Locatelli and Y. Manzoni, *Carbonai e boscaioli: l'emigrazione bergamasca sulle Alpi occidentali dal diciannovesimo al ventesimo secolo*, Sant'Omobono Terme, 2005, 282.

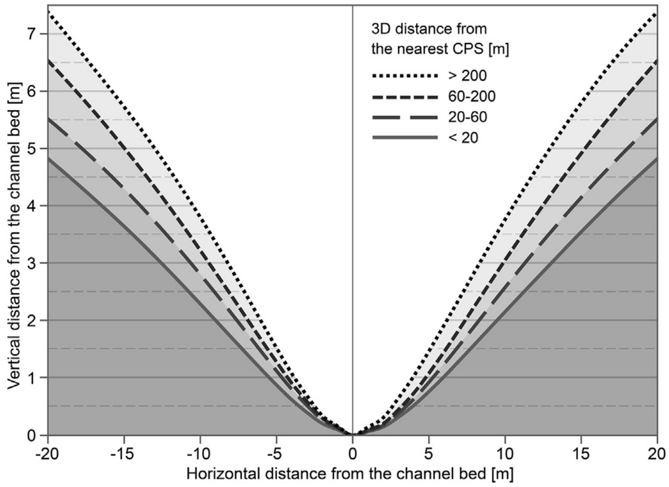


**Fig. 7.** Variability of the average transverse elevation profile of the stream channels for four categories of three-dimensional distance between the axis of the channel and the nearest CPS.

for charcoal makers because water was used to regulate wood pyrolysis, stop combustion and prevent the spread of fire, as well as for domestic needs (washing, cooking and drinking). It must be remembered, however, that the excessive use of water during carbonization or cooling could easily spoil the quality of the product. For this reason, skilled charcoal burners preferred to use earth for the quenching of fires, and used water sparingly as a last resort to regulate and stop the pyrolysis and combustion reactions.[44]

Protection from wind could also be an important reason to prefer concave sites.[45] All written reports on wood carbonization clearly state that wind and strong air currents may have a serious negative impact on charcoal production (see factor 27 in Table 2). The negative effects of breezes (slight and moderate air currents) could be controlled and minimized by constructing simple screens of twigs and leafy branches.[46] However, these makeshift shelters are insufficient against strong winds. It is, therefore, essential to choose well sheltered positions on the slope.

Soil characteristics also have a great influence on the proper functioning of the charcoal kiln (see factors 1–8 in Table 2). Charcoal makers thus had to pay close attention to the soil, especially in mountainous environments, where soil characteristics change constantly and rocky outcrops are frequent. As early as the sixteenth century it was recommended that CPS should have ‘good and strong soil’ suitable as ground and as cover for the wood pile.[47] Some authors suggest avoiding moist or swampy soil in favor of dry soil.[48] Soil thickness is an important factor in itself because of the great volume of earth needed to build up a proper platform and cover the charcoal kiln. Generally, soil is deeper in areas of convergent topography which is an additional advantage offered by

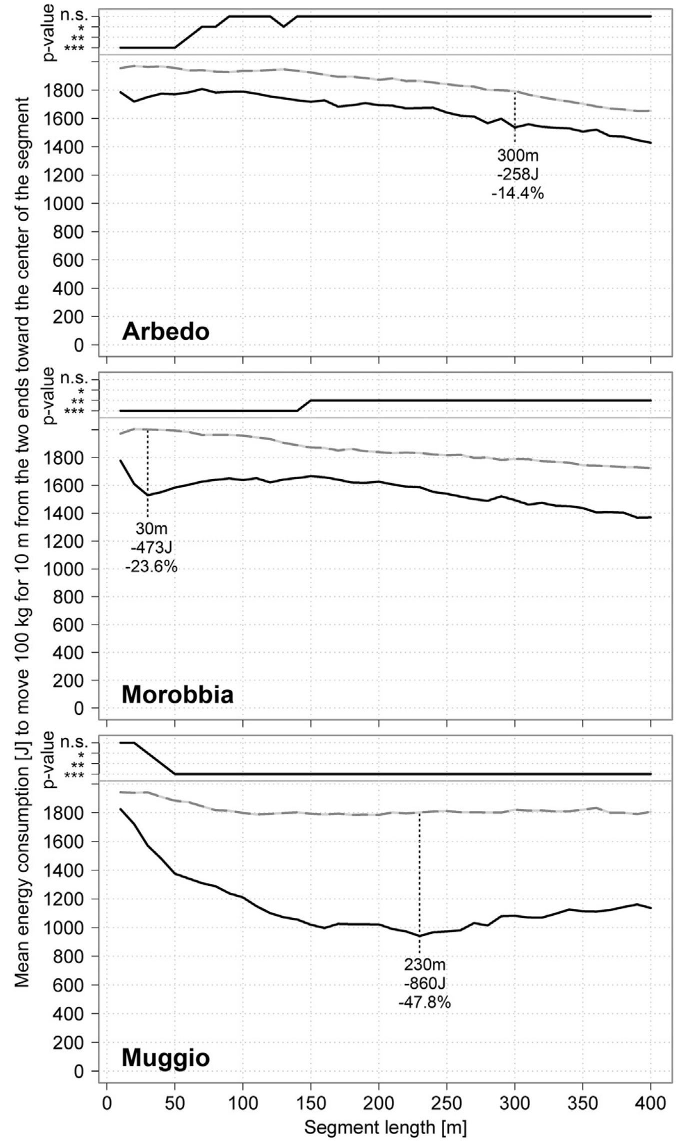


**Fig. 8.** Mean energy consumption (joules) required to move 100 kg a distance of 10 metres from the two ends toward the center of the TEP. The figure shows the difference between charcoal production sites (solid black line) and random points (dashed gray line) in the three study areas according to segment length (from 10 to 400 metres). Vertical dotted lines indicate the maximum differences. In the upper part of each graph, the significance of the difference between CPS and random points is presented with reference to p-values (Wilcoxon signed rank test). Here, a low coefficient of kinetic friction is used (ckf = 0.2) and the ideal situation where all the kinetic energy is exploited to reduce overall energy consumption is assumed.

concave sites.[49]

For similar reasons, concavity could be advantageous for wood charcoal production even with reference to the longitudinal terrain profile. For instance, locating the site of carbonization at the beginning of a lower slope or foot slope allowed the charcoal burner to benefit from many advantages such as deeper soil and more stable and less steep ground, providing more space for the

[44] S. Toffenetti, I carbonai dell’Appennino, unpublished master's thesis, Università degli Studi di Bologna, 1993, 78.

[45] S. Olivari, *Quando sul monte si cuoceva il carbone: la produzione del carbone di legna nel Monte di Portofino*, Recco, 2007, 19.

[46] See the ‘moveable skreen’ in E. Chambers, *Cyclopædia, or, an Universal Dictionary of Arts and Sciences*, London, 1728, volume 1, 200.

[47] See ‘terra buona e tenace’ in Biringuccio, *De la pirotechnia*, 62; and ‘terra buona et tenace’ in T. Garzoni, *La piazza universale di tutte le professioni del mondo*, Venezia, 1585, 799.

[48] See for instance ‘auf keinen feuchten oder morastigen sondern auf trocken Boden’ in Carlowitz, *Sylvicultura oeconomica*, 252.

[49] A.M. Heimsath, W.E. Dietrich, K. Nishiizumi and R.C. Finkel, Cosmogenic nuclides, topography, and the spatial variation of soil depth, *Geomorphology* 27 (1999) 151–172; J. Braun, A.M. Heimsath and J. Chappell, Sediment transport mechanisms on soil-mantled hillslopes, *Geology* 29 (2001) 683–686.

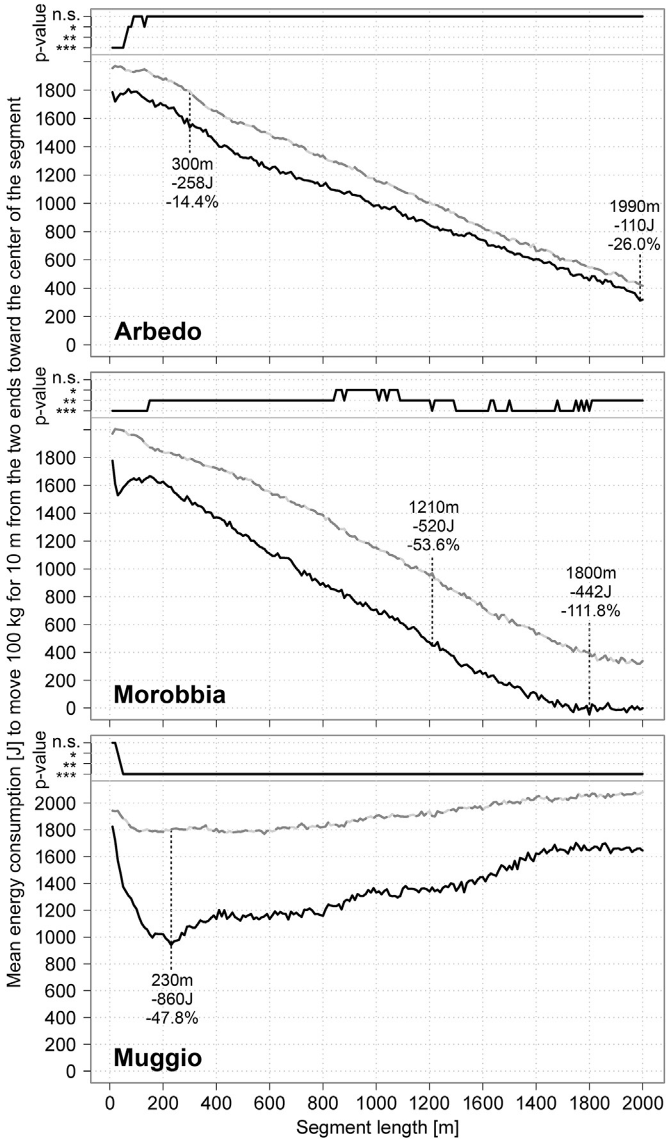


**Fig. 9.** The same as Fig. 8, but with a general view including longer segment lengths of up to 2000 metres.

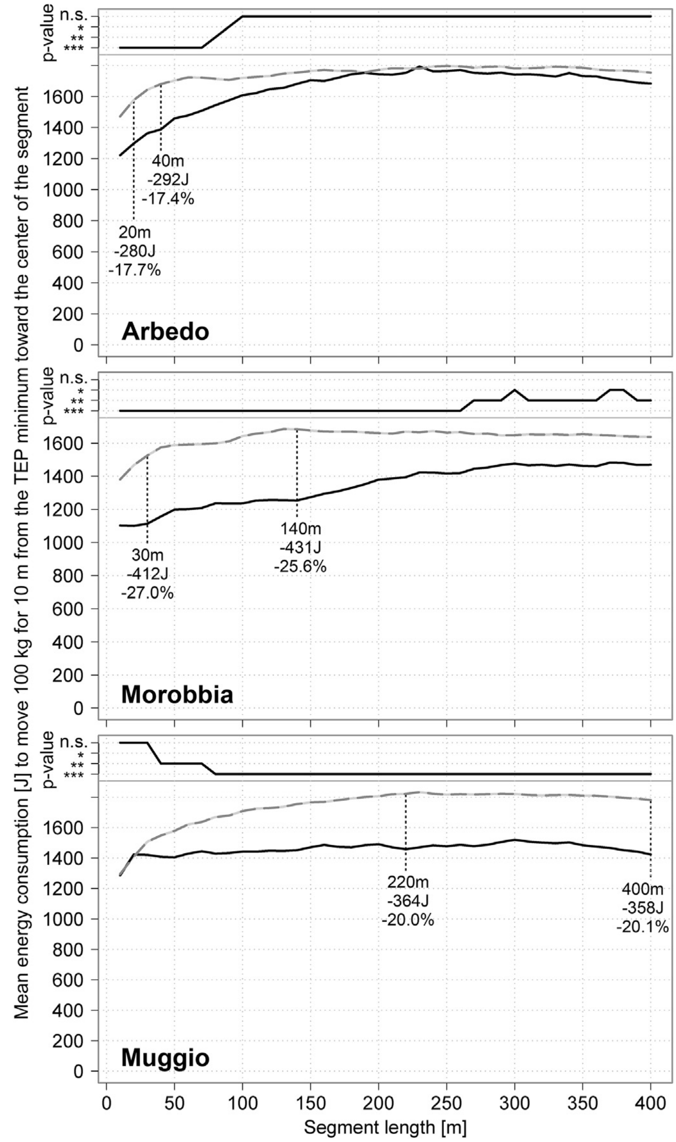


**Fig. 10.** Mean energy consumption (joules) to move 100 kg a distance of 10 metres from the lowest point of the TEP toward its centre. The figure shows the difference between charcoal production sites (solid black line) and random points (dashed gray line) in the three study areas according to segment length (from 10 to 400 metres). Vertical dotted lines indicate the maximum differences. In the upper part of each graph, the significance of the difference between CPS and random points is presented with reference to p-values (Wilcoxon signed rank test). Here, a high coefficient of kinetic friction is used (ckf = 0.4) and kinetic energy exploitation to reduce overall energy consumption is assumed to be half.

charcoal kiln and added structures (see factors 10–14 in Table 2).[50]

Concave sites may also have disadvantageous characteristics. Specifically, CPS located at the bottom of a stream channel or a valley are exposed to floods that can damage or demolish the platform. This was a significant threat that forced charcoal burners to comply with a safety distance when building CPS near a permanent or temporary watercourse (see factor 26 in Table 2). Considering the rain regime of southern Switzerland, characterized by heavy rain episodes up to a maximum daily rainfall of 200–400 mm in twenty-four hours, it is likely that over long periods of time this safety distance may have been found to be insufficient to protect CPS against the destructive effect of floods.[51]

It is reasonable to assume that many CPS located in concave positions were not discovered and recorded during our comprehensive mapping because they had been completely destroyed by floods. CPS located on ridges (on nose-shaped slopes or other divergent landforms), in contrast, have better chances of being spared from destructive processes.[52] In this sense, it is likely that our results have been affected by this differentiated destruction probability. If the present study had been conducted one hundred years ago, immediately after the abandonment of the platforms, we would most likely have obtained an even stronger result in terms of

[50] J. Gerrard, *Fundamentals of Soils*, London, 2000, 40.

[51] G. Pedrozzi, Triggering of landslides in Canton Ticino (Switzerland) and prediction by the rainfall intensity and duration method, *Bulletin of Engineering Geology and the Environment* 63 (2004) 281–291.

[52] The soil erosion due to surface runoff is usually stronger on convex hillslopes. But the damage produced by surface runoff on CPS, even in the long run, are usually less serious than the impact of a single flood event.

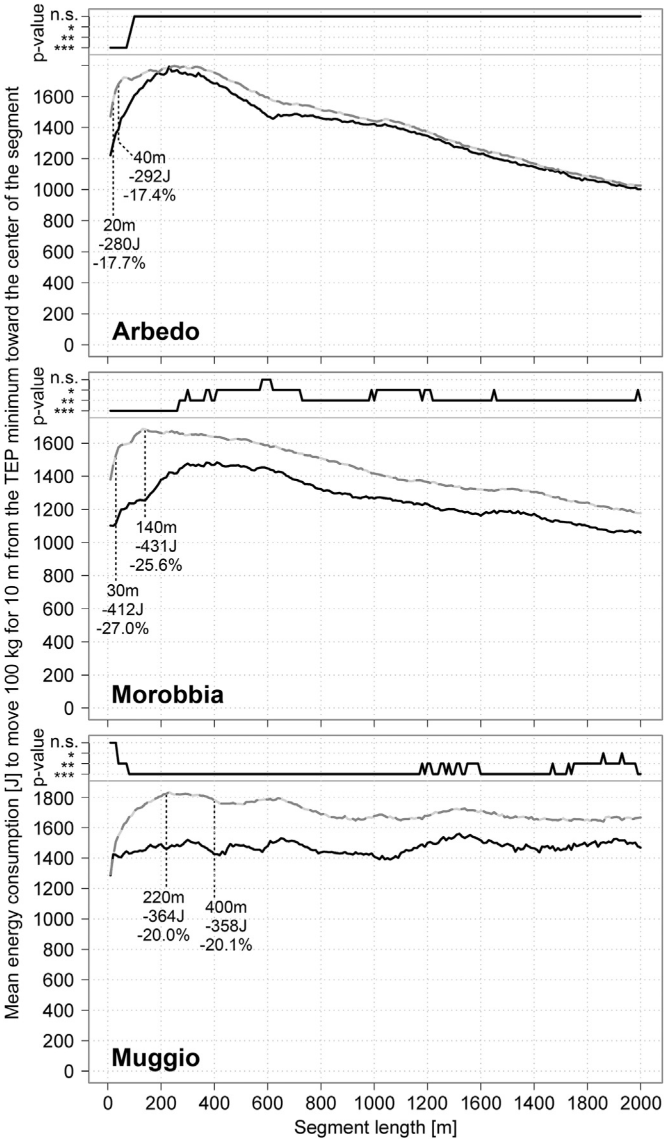


**Fig. 11.** The same as Fig. 10, but with a general view including longer segment lengths of up to 2000 metres.

the concentration of carbonization places in concave sites.

*Accounting for differences among study areas*

The differences and exceptions in CPS distribution highlighted by our results at the local and regional level suggest that the general rules discussed thus far may not apply everywhere in the same way, nor with the same positive outcomes in terms of work efficiency. In the Alps, the attraction of natural drainage channels for CPS may be limited by the high roughness of the relief. In the valleys of southern Switzerland in particular, the relationship between CPS and drainage bottom is not obvious and may be highlighted only through an in-depth analysis of geographic data. In fact, many segments of run-off channels and valleys are too steep, deep, narrow and rocky to serve as transportation routes for firewood or to offer suitable locations for CPS. In these cases the charcoal burners were forced to consider other locations, including those at a considerable distance from the channels (Figs. 6 and 7). The effect of such a limiting factor is partly reflected in the different results obtained in our three study areas, which can be placed along a roughness gradient from the Alpine foothills (Muggio, mean slope of concave sites 26°) to the main Alpine ridge (mean slope of concave sites 30° in Morobbia and 31° in Arbedo, respectively). This is also confirmed by the fading trend in the statistical distinction between CPS and RP in terms of energy consumption for wood transportation when the relief becomes more pronounced (Figs. 8–11).

Consequently, we are not surprised to find, outside the Alps, cases showing relationships between CPS and the natural drainage network that are stronger than those found in our study. This is the case, for instance, in Harz, a low-mountain range in southern Lower Saxony (northern Germany) characterized by a mildly hilly terrain with a maximum elevation of 1141 metres.[53] The low-mountain region of the Palatinate Forest in southwestern Germany shows similar patterns.[54] In comparison to these two German areas, in our alpine case study the roughness of the topography and the intensity of rainfall are high enough to substantially weaken the tendency of CPS to cluster along the drainage bottom.

The influence of factors such as environmental context, terrain roughness and climate on the relationship between CPS and stream network can also be found outside Europe. In the southern valleys of the Robert's Creek Mountain (3089 m.a.s.l) in central Nevada, Reno described a very strong correlation between CPS and wash bottoms. In this case the altitude and the roughness of the relief are considerable. However, as stated by the author, the risk of flooding is low because of an annual average rainfall of 300 mm, the ridges have a very low tree cover due to dryness, and the channels ‘comprise the gentlest terrain’ in the study area.[55] Moreover, CPS were built in a virgin land and exploited over a very short period of time (1860–1890) in an economic context dominated by industrial capitalism and devoted to the optimization of production processes.

Returning to southern Switzerland, in Muggio and Morobbia valleys (that is, two out of the three study areas) the differences in energy consumption between CPS and RP remain significant even for long transverse elevation profiles (Figs. 9 and 11). This result seems to indicate that even at the large spatial scale of the whole hillslope or valley CPS are not randomly distributed. In fact, in Muggio and Morobbia valleys the concentration of CPS is slightly higher on lower and foot slopes than on upper and middle slopes.[56] Given this distribution pattern it seems reasonable to suppose that the CPS located at lower and foot slope positions were supplied not only with wood coming from the immediate vicinity of the carbonization site, but also with wood transported over longer distances, especially along natural drainage channels.

*Limits of the approach*

In Europe, charcoal production activities generally fell drastically before the end of the nineteenth century, although there was a remarkable revival of wood charcoal production during the two world wars, even if limited in time and space. However, once the Suez crisis of 1956 was over the decline became terminal so that the main actors in this industry have disappeared, leaving only the

[53] Hillebrecht, *Die Relikte der Holzkohlewirtschaft*, 45 and 53; Kortzfleisch, *Köhlerei im Harz*, figure A IX.

[54] Hildebrandt, Heuser-Hildebrandt and Wolters, *Kulturlandschaftsgenetische und bestandsgeschichtliche Untersuchungen*, Figs. 1 and 2.

[55] Reno, Fuel for the frontier, 262 and 264.

[56] Evidence in this sense is provided by Krebs, Stocker, Pezzatti and Conedera, An alternative approach. See in particular Figure B.5 in Appendix B in the supplementary material.

charcoal production platforms as evidence of their work.[57] In addition, charcoal burners were almost all illiterate, so that most written sources on the wood charcoal proto-industry were produced by learned observers and commentators who were probably not directly involved in the production cycle of wood charcoal. The proliferation of essays on the art of charcoal burning mainly arises from the new intellectual forces of the Age of Enlightenment. It is likely that in some cases the treatises of those distinguished writers were dictated mainly by their exuberant rationality rather than from precise and unbiased observations of the real solutions adopted in the field by charcoal makers. Moreover, most of this literature was conceived in relation to flat or moderate hilly landforms and not for regions with a rough relief such as the Alps. Therefore, there is likely to be a consistent gap between the conceptual and ideal organization of charcoal burning promoted by these writers and what was put into practice by charcoal makers. In this sense, the analysis of the distribution of CPS on the land surface is an indispensable way of obtaining and formulating a reliable answer to our initial questions, and must be jointly considered with the analysis of written sources.

The issue is further complicated by the fact that the choice of carbonization sites was not a matter for charcoal makers alone. In some European countries, such as France and Switzerland, at least starting in the seventeenth century, there were public officials that set rules for the localization of CPS. In some cases a maximum number of CPS was imposed for each cutting surface. Alternatively, CPS were visited and marked by public officials who had the power to ban certain places and enforce others. For instance, in 1668 the mayor of the municipality of Giornico in southern Switzerland had to check that carbonizations took place far from valuable grazing land. In other cases, the aim of the inspection was fire prevention by ensuring the absence of flammable brushwood close to CPS.[58]

It is also important to recognize that the current distribution of CPS is often the result of the work of many generations of charcoal burners. On the one hand, every new generation was inclined to reuse old CPS, especially in order to save construction time and to benefit from better soil conditions.[59] On the other hand, every generation was prone to introduce changes with the aim of improving the workflow, which resulted in the development of the process of charcoal production over time. Extreme examples of sophisticated workflow organization may be found in logging companies in the second half of the nineteenth century that benefited from process optimizations that resulted from the industrial revolution.[60]

Despite common characteristics, every study area shows a specific distribution pattern. In order to understand this variability the distribution of CPS must be approached as a complex phenomenon. Our analysis has focused on terrain curvature and on its consequences, especially in terms of energy spent in wood dragging. Presumably, these factors represent only a part of the range of factors that influence the balance between the advantages and disadvantages of particular CPS. The selection of CPS was in all likelihood based on a multi-factor evaluation of sites. A site that was excellent in terms of terrain curvature could have been discarded because of inadequate soil stability, soil composition, water availability, flood safety, fire safety or location with respect to the footpath network. Moreover, the forests used by woodcutters and charcoal makers were very diverse in terms of species composition, accessibility, topography (slope, aspect) and soil conditions. Consequently, the rules followed for the selection of carbonization sites could not be applied blindly, but required adaptation to the considerable diversity of spatial and environmental conditions.

## Conclusions

Our results clearly demonstrate that charcoal burners followed some objective criteria when choosing and preparing places for carbonization. In particular, they carefully considered their relative position on the terrain surface with respect to the main topographic and morphometric features. In general, we observe that the number of CPS per unit of surface area is higher in proximity to the bottom of runoff channels, while it is lower close to the top of ridges. On the basis of the analysis of written sources, it can be asserted that this distribution pattern was pursued so as to facilitate the work of wood transportation, as well as to benefit from good water availability and good wind protection. That is, to substantially comply with at least three out of the four most important qualities required for CPS. Through simulations of energy consumption for mass transport along transverse elevation profiles we have demonstrated the significant advantages in terms of energy inputs for wood transport operations offered by the CPS locations with respect to random points. Beyond this general trend, it must be recognized that our results also suggest a number of exceptions. Even for the study area with the most significant results, some CPS are located close to the highest point of the transverse profile in a disadvantageous position for the transport of wood. The interpretation of these exceptions is delicate. It is certain that charcoal burners did not act as calculating machines and the contributions of randomness and improvisation in their choices are likely to be relevant.[61] On the other hand, we are convinced that most of the apparent disorder in the distribution of CPS is simply due to the difficulty in considering in full the wide range of site conditions that could influence the choice of CPS locations. For instance, the comparison between areas with different topographic characteristics highlights the key role played by the average slope of stream channels in determining the tendency of CPS to cluster along the drainage bottom. In particular, our analysis reveals that the most attractive stream channels to CPS are those with a smooth profile, with quite gentle slopes (<30° average slope) and a rather high flow accumulation (>70 ha). CPS distribution patterns therefore depend on the

[57] In some regions of Europe it is still possible to find the last charcoal burners at work. But nowadays the methods and the instruments used are no longer the same as they were a century ago. See for instance M. Huwyler and M. Bühler-Rasom, Altes Handwerk. Houzchole vom Napf, *Schweizer LandLiebe* 3, 1 July 2013, 116–121 for central Switzerland; M. Corona, Ultimi carbonai, in: *Nel legno e nella pietra*, Milano, 2003, 188–192 for northern Italy; D. Guzzardi and M. Greco, Il carbone del Cremlino, *Il Quotidiano della Domenica*, 15 November 2015, 45–47 for southern Italy; M. Waldstein and M. Horvath, Köhler. Das Feuer regieren, *Schaufenster Kultur-Region*, April 2013, 46–48 for the Wiener Neustadt-Land district of Lower Austria; J.A. Cardenal Galván, J.M. Crespo Martín, D. Peral Pacheco and J.R. Vallejo Villalobos, Fabricando combustível natural. Carvoarias e fornos de carvão vegetal, in: M.J. Palacios González, J.A. Díaz Caballero and P. Muñoz Barco, *Guardiana internacional. Cultura y biodiversidad entre cañones y valles olvidados*, Mérida, 2011, 227–241 for Extremadura in Spain.

[58] See for instance M. Pedrazzini and C. Conti, *Regolamento comunale e patriziale di Bodio*, Locarno, 1878, 3.

[59] S. Paradis-Grenouillet, P. Allée, G. Servera Vives and A. Ploquin, Sustainable management of metallurgical forest on Mont Lozère (France) during the Early Middle Ages, *Environmental Archaeology* 20 (2015) 179. See also 'benöthigte Kohl-Gestübe' and 'besten guten Erde' in Carlowitz, *Sylvicultura oeconomica*, 252.

[60] See for instance Reno, Fuel for the frontier, 262.

[61] Some authors report cases of CPS located in extreme conditions, such as very steep and rocky terrain. See R. Rouaud, Les forêts de pente de la haute vallée de la Dordogne: enjeux écologiques et énergétiques d'une ancienne forêt charbonnée (Auvergne, Limousin, France), unpublished PhD thesis, Université de Limoges, 2014, 180–181.

roughness of the relief and on the conditions of slope and accessibility offered by runoff channels in particular which played a key role in the past as conveyor tracks for the transport of firewood. From this point of view, it would be desirable to focus future research on the verification and specification of this relationship in different mountainous regions in the world.

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## Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jhg.2017.04.002.