UNIVERSITÀ POLITECNICA DELLE MARCHE

DOCTORAL THESIS

C and nutrients storage in long-time managed forest ecosystems subjected to land-use changes

Author

Lorenzo Camponi

May 6th, 2023

Università Politecnica delle Marche

Ph.D. Course in Agriculture, Food and Environmental Sciences

UNIVERSITÀ POLITECNICA DELLE MARCHE
Department of Agriculture, Food and Environmental Sciences (D3A)
Division: AGR/14 – Pedology

Ph.D. IN AGRICULTURE, FOOD AND ENVIRONMENTAL SCIENCE

Scientific field: Soil Science

XXXV (35°) course (2019 – 2022)

C and nutrients storage in long-time managed forest ecosystems subjected to land-use changes

Ph.D. Candidate:

Lorenzo Camponi

Advisor:

Prof. Giuseppe Corti

Co-advisor:

Prof. Stefania Cocco

May 6th, 2023

Dedico questa tesi a mio padre *Franco* e mia madre *Emanuela*

Acknowledgements

Dopo tre anni e spicci spesi in questo percorso credo che il minimo sia tirare le somme di tutto ciò che è stato. Il dottorato si è dipanato in un lasso di tempo nel quale ho potuto confrontarmi con due grandi personaggi: la vittoria e la sconfitta. Sono stati sicuramente due grandi impostori ai quali devo ammettere di aver creduto con eguale convinzione. Sicuramente avrei potuto fare molto di più di quello che presento in questa tesi, ma in alcuni momenti ho anche pensato che non sarei riuscito a fare proprio un bel niente. Vorrei cristallizzare in questo lavoro non solo il risultato di tre anni di lavoro tramite dei numeri e delle parole, ma anche e soprattutto in questa sezione, tutto quello che questo percorso ha rappresentato per me su un altro piano: quello delle emozioni e dei sentimenti. Elementi che penso distinguano un essere umano da un calcolatore e che vorrei esprimere ringraziando chi c'è sempre stato più o meno fisicamente.

Ringrazio innanzitutto la mia famiglia, mio padre e mia madre, che mio malgrado mi hanno sempre sostenuto emotivamente ed economicamente e spinto a studiare e ad impegnarmi nell'aumentare le mie conoscenze, senza i lori sforzi a quest'ora con buona probabilità non sarei qui a fare quello che sto facendo.

Vorrei ringraziare i miei tutor, *Giuseppe Corti* "Beppe" e *Stefania Cocco* "Stefi", che poi sono un po' come mamma e papà nel mondo accademico, che mi hanno sempre accolto e stimolato a fare di più e soprattutto non mi hanno mai fatto sentire l'effettivo divario in termini di conoscenze e posizione, dandomi anzi sempre la possibilità di mettermi alla prova e contribuire attivamente alla vita del gruppo.

Un ringraziamento speciale lo faccio ai miei colleghi e soprattutto amici, "Lo scienziato pazzo" *Andrea Salvucci*, "Il generalissimo" *Dominique Serrani* e "Mamma Vale" *Valeria Cardelli*, per i quali nutro un sentimento di profondo affetto e con i quali ho condiviso tutti i disagi e le gioie lavorative e non, Grazie!

Infine, vorrei ringraziare tutti le persone che hanno fatto e che fanno ancora parte della mia vita, che mi sono state vicine in questo percorso, non li nomino tutti altrimenti scrivo un'altra tesi, ma sono tutti quelli con cui mi metto le mani in faccia la sera, vado a fare baldoria e passo il mio tempo libero, Grazie!

Lorenzo

List of publications

1. Camponi, L., Cardelli, V., Cocco, S., Serrani, D., Salvucci, A., Cutini, A., Agnelli, A., Fabbio, G., Bertini, G., Roggero, P.P., Corti, G., 2022. Effect of coppice conversion into high forest on soil organic C and nutrients stock in a Turkey oak (Quercus cerris L.) forest in Italy. J. Environ. Manage. 312. https://doi.org/10.1016/j.jenvman.2022.114935
2. Camponi, L., Cardelli, V., Cocco, S., Serrani, D., Salvucci, A., Cutini, A., Agnelli, A., Fabbio, G., Bertini, G., Roggero, P.P., Weindorf, D.C., Corti, G., 2023. Holm oak (Quercus ilex L.) cover: A key soil-forming force in controlling C and nutrient stocks in long-time coppice-managed forests. J. Environ. Manage. 330. https://doi.org/10.1016/j.jenvman.2022.117181
3. Salvucci, A., Cocco, S., Agnelli, A., Cardelli, V., Camponi, L., Serrani, D., Corti, G., 2023. Genesis and preservation of patterned ground in permafrost non-affected soils – Central Apennines, Italy. Geoderma Reg. 32. https://doi.org/10.1016/j.geodrs.2022.e00604
4. Salvucci, A., Serrani, D., Agnelli, A., Cardelli, V., Camponi, L., Corti, G., Cocco, S., (*under review*). Impact of agricultural management on salts accumulation in dryland soils of central Tunisia.

Thesis Declaration

I, Lorenzo Camponi, certify that:

- This thesis has been substantially accomplished during enrolment in the degree.
- This thesis does not contain material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution.
- No part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution.
- This thesis does not contain any material previously published or written by another person, except where due reference has been made in the text.
- The work(s) are not in any way a violation or infringement of any copyright, trademark, patent, or other rights whatsoever of any person.
- This thesis contains published work and/or work prepared for publication.

Signature: 

Date: 6th May 2023

Abstract

Land Use Change (LUC) is a process that modify the Earth surface as a consequence of human activities and that could be a driver for socioeconomical and environmental changes. In agricultural sciences LUC could affects the land cover (expansion or contraction) or type of management on an already existing cover. LUC influence deeply also the forest ecosystems (e.g. changes in the canopy structure, management of residues, grazing or fertilizing) that are the principle soil-keeper environments and the major carbon and nutrients sink of our Planet. In particular forest soils are able to store an amount of C and nutrients like N, P and others by far higher than that in aboveground biomass and atmosphere. Thus, the aim of this thesis is to evaluate the impact of LUC in forest ecosystems, in particular: i) How a different intensity canopy density management (thinning) recently applied (≈70 y) influence the soil organic C and nutrients (N, P, Ca, Mg, K) storage capacity in similar forests; ii) How a millennial management in similar forests influence organic C and nutrients (N, P, Ca, Mg, K) storage capacity in soils developed on different parent materials; iii) How a differentiate management and forest botanical stand composition affect the organic C storage in aboveground biomass, soil and roots; iv) How a differentiated management affect the soil organic C stock and its density fractions. After survey campaigns, soil samples were analysed and the stock of C and nutrients were calculated following a standardized procedure.

The soil stock of C and appeared to be slightly influenced by thinnings operated in the last 70 years of management compared to three millennia of forest use. Basically forest cover and human activity are the main soil forming forces. The stocks of organic C and nutrients in the soils under long-time managed forests were little influenced by parent materials. The long-time during which plants have modified the soil properties trough acidification, mineral weathering, SOM addition, and biocyling of nutrients have reduced the influence of the parent materials on the soil properties making them similar. Organic C stock in aboveground biomass, litter, mineral soil and roots of broadleaves forests subjected to a differentiate management depends on plant-site relation, stand

biological characteristics and management practices. The monitoring activity conducted in a forest subjected to a differentiated management on total and fractionated organic C stock showed a strict connection between the cenosis, the site features, the soil properties and the management.

Contents

INTENTIONALLY LEFT BLANK

CHAPTER 1 - INTRODUCTION

1.1. Land Use Change

The land use change (LUC) is generally described as the phenomenon of Earth surface modification related to human activities such as agriculture, forestry, and building construction that alter land surface processes including biogeochemistry, hydrology, and biodiversity (Ellis, 2007).

At global scale, as reported by FAO (2020), agricultural land area is approximately five billion hectares (almost 38% of the global land surface) and one-third of this is used as cropland, while the remaining two-thirds consist of meadows and pastures for grazing livestock. In this complex land management framework, LUC is an important driver of change in both environmental and social structure. Lambin & Geist (2003) highlighted that from society's point of view, LUC determines from one point of view a vulnerability to economic and political perturbances but also an increase in food and fibre production, a better use of resources and consequently an improvement in wealth and well-being.

In agricultural sciences, LUC could be ascribed to two major phenomena: i) a change in land cover associated with the expansion or contraction of the area of land used for different purposes (e.g., pasture, cropland, urban); ii) a change in the type of management on existing land cover (e.g., changes in irrigation, fertilizer use, crop type, harvesting practices, or impermeable surfaces) (Davis et al., 2019).

Regardless of LUC phenomena typology, landscape deep modification process has a strong influence on pedogenesis and consequently on soil physical, chemical, and biological properties like pedofauna biodiversity, structure, texture, pH, C content, etc. (Geissen et al., 2009; Haghighi et al., 2010; Adam et al., 2014) As suggest by Burst et al. (2020), soil properties vary spatially according to land use; both because land users have selected specific soil properties for specific land uses, and land uses modify the soil properties.

LUC influence on soil physicochemical properties has indeed been demonstrated to occur since the Holocene and, later, in bronze and Roman ages in Europe. In fact, soil erosion after forest clearing and badlands landscape dynamics are clear and worldwide spread examples of this phenomenon (Burst et al., 2020; Cocco et al., 2015; Hassink, 1994; Houben, 2008; Laganière et al., 2010; Zucca et al., 2010). Specific examples of such influences are the effects on soil texture: a change in the distribution of very large and large pores contributes to less than 1% of the soil volume, but more than 50% in the total soil water flow (Baranian Kabir et al., 2020); chemical properties like soil organic carbon content (SOC) are also affected: the change in land use from a natural environment (e.g., marshes) into a farmlands induces a reduction of SOC storage of 56%–60% within 5 years (Ouyang et al., 2013; Zhang et al., 2019).

The effects of LUC are also appreciable on soil biota, for example on soil mesofauna: the mite species abundance is strongly related to land use type (Minor and Cianciolo, 2007) or, as reported by Schneider et al. (2015), to soil microbial component: the conversion from natural ecosystems (e.g. rainforest, Indonesia) to a farmland (e.g. rubber plantation) significantly changes bacterial community structure.

1.2 Soil organic carbon and nutrients content in forest ecosystems

In every Earth ecosystem, whether it is aquatic or terrestrial, soil plays a key role in regulating the fluxes of elements as C, N, etc. In particular in forest ecosystems, the input of organic matter comes from plants (e.g., litter, roots, and branches) (Lehmann et al., 2015; Diao et al., 2020; Wu et al., 2020). The plant-derived organic materials through many physicochemical and biological transformation are transformed in soil organic matter (SOM). The plant-soil interaction is determinant in SOC and other nutrients like N and P stock (Tiessen et al., 1994). Estimations indicate that the global organic C and N soil content to 1-m depth is 1462-1548 Pg and 133-140 Pg, respectively (Batjes, 1996), an amount that is significantly higher than the sum of the same elements stocked in vegetation and atmosphere (Lehmann et al., 2015; Mayer et al., 2020).

The stock of C in forest soils until 1 m depth is estimated to be 383 ± 30 Pg C at global scale (Pan et al., 2011). Organic C cycling in forest soils and the capacity of these ecosystems to stock this element influence their functionality, contrast climate change, and contribute to a sustainable forest management (Cutini et al., 2021). The fundamental role of C in soils is also linked to N and P cycles (Innangi et al., 2017; Vindušková et al. 2019). In fact, organic C mineralisation is strongly related to N and P availability and their ratios because of their influence on the abundance and activity of the soil microbial community (Kirkby et al., 2013; Zheng et al., 2021). N in the terrestrial ecosystem becomes available for biological processes through atmospheric N_2 fixation in the soil, and subsequently via decomposition and mineralization of SOM by soil pedofauna (De Nobili et al., 2020) and microbial communities (Alarcón-Gutiérrez et al., 2008). the main source of soil P are rocks, and weathering processes (Walker and Syers, 1976) lead to P release in soils in form of frequently low solubility phosphatic salts or in organic forms (Arenberg and Arai, 2019).

1.3 Effects of management on C and nutrients soil forest stock

In forest ecosystems, plants management may impact on organic C and nutrient stock. As highlighted by Mayer et al. (2020), management practices (e.g., site preparation, harvesting operations, removal of harvest residues and litter) for different purposes have a negative impact on soil nutrients storage capacity. Planting N-fixing plants, nitrogenous fertilizations and moderate grazing have a positive impact on SOC storage. Management of tree species diversity and periodical thinnings in high forests and in the conversion into high forest of coppices did not modify soil capacity to stock SOC under both broadleaves and conifers (Bravo-Oviedo et al., 2015; Prasad Dangal et al., 2017; Zhang et al., 2018; Mayer et al., 2020).

A widespread example of European forest management is coppicing, which represents the oldest form of systematic and sustainable use of forests. It is a very flexible system that requires a low energy input and has been adapted and modified according to the needs of rural societies, to whom coppice forests deliver small size wood primarily for energy (firewood and charcoal), agriculture, and small-scale businesses. Because of the social and economic crisis of that system, the conversion of coppices into high-forests is considered a sustainable forest management in many countries (Fabbio, 2016; Fabbio and Cutini, 2017; Cutini et al., 2021) due to the less soil disturbance that would favour SOC storage (Hölscher et al., 2001; Marchi et al., 2016). Thus, forest management influence on soil, has fostered many scientific researches (e.g., Caddeo et al., 2019; Zhang et al., 2019; Zhao et al., 2019; Lee et al., 2020).

2. Aim of the thesis

The object of this thesis is the evaluation of the impact of LUC on different soil properties and in particular the capacity to store organic C and other nutrients. In particular, the research question are:

1. What is the impact of management in similar forests subjected to different population regulation treatments on soil organic C and nutrients (N, P, Ca, Mg, K) storage capacity?
2. What is the impact of the management on the soil organic C and nutrients (N, P, Ca, Mg, K) storage capacity in similar forests with soils developed on different parent materials?
3. What is the impact of management on forest soil capacity to store organic carbon in fine earth, rock fragmetns, and roots compare to aboveground biomass of different typology developed on the same parent material?
4. What is the impact of differentiated forest management on SOM fractions storage capacity?

References

Alarcón-Gutiérrez, E., Couchaud, B., Augur, C., Calvert, V., Criquet, S., 2008. Effects of nitrogen availability on microbial activities, densities and functional diversities involved in the degradation of a Mediterranean evergreen oak litter (Quercus ilex L.). Soil Biology and Biochemistry. 40, 7, 1654-1661. https://doi.org/10.1016/j.soilbio.2008.01.020.

Arenberg, M.R., Arai, Y., 2019. Uncertainties in soil physicochemical factors controlling phosphorus mineralization and immobilization processes. Adv. Agron. 154, 153–200. https://doi.org/10.1016/BS.AGRON.2018.11.005

Baranian Kabir, E., Bashari, H., Bassiri, M., & Mosaddeghi, M. R. (2020). Effects of land-use/cover change on soil hydraulic properties and pore characteristics in a semi-arid region of central Iran. Soil and Tillage Research, 197, 104478. https://doi.org/10.1016/J.STILL.2019.104478

Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. Eur. J. Soil Sci. https://doi.org/10.1111/ejss.12114_2

Burst, M., Chauchard, S., Dambrine, E., Dupouey, J.-L., & Amiaud, B. (2020). Distribution of soil properties along forest-grassland interfaces: Influence of permanent environmental factors or land-use after-effects? Agriculture, Ecosystems & Environment, 289, 106739. https://doi.org/10.1016/J.AGEE.2019.106739

Cocco, S., Brecciaroli, G., Agnelli, A., Weindorf, D., Corti, G., 2015. Soil genesis and evolution on calanchi (badland-like landform) of central Italy. Geomorphology 248, 33–46. https://doi.org/https://doi.org/10.1016/j.geomorph.2015.07.031

Cutini, A., Ferretti, M., Bertini, G., Brunialti, G., Bagella, S., Chianucci, F., Fabbio, G., Fratini, R., Riccioli, F., Caddeo, C., Calderisi, M., Chiucci, B., Corradini, S., Cristofolini, F., Di Salvatore, U., Ferrara, C., Frati, L., Landi, S., Marchino, L., Patteri, G., Piovosi, M., Roggero, P.P., Seddaiu, G., Gottardini, E., 2021. Testing an expanded set of sustainable forest management indicators in Mediterranean coppice area. Ecological Indicators. 130, 108040. https://doi.org/10.1016/j.ecolind.2021.108040

Diao, M., Yang, K., Zhu, J., Li, M., Xu, S., 2020. Native broad-leaved tree species play key roles on maintaining soil chemical and microbial properties in a temperate secondary forest, Northeast China. Forest Ecology and Management. 462, 117971. https://doi.org/10.1016/j.foreco.2020.117971

Davis, K.F., Dalin, C., DeFries, R., Galloway, J.N., Leach, A.M., Mueller, N.D., 2019. Sustainable Pathways for Meeting Future Food Demand. In: Ferranti, P., Berry, E.M., Anderson, J.R. (Eds.), Encyclopedia of Food Security and Sustainability, vol. 3, pp. 14–20. Elsevier. ISBN: 9780128126875

De Nobili, M., Bravo, C., Chen, Y., 2020. The spontaneous secondary synthesis of soil organic matter components: A critical examination of the soil continuum model theory. Appl. Soil Ecol. 154, 103655. https://doi.org/10.1016/j.apsoil.2020.103655

Ellis, Erle (Lead Author); Robert Pontius (Topic Editor). 2007. "Land-use and land-cover change." In: Encyclopedia of Earth. Eds. Cutler J. Cleveland (Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment). [First published July 17, 2006; Last revised January 31, 2007; Retrieved May 3, 2007].

Geissen, V., Peña-Peña, K., Huerta, E., 2009. Effects of different land use on soil chemical properties, decomposition rate and earthworm communities in tropical Mexico. Pedobiologia (Jena). 53, 75–86. https://doi.org/https://doi.org/10.1016/j.pedobi.2009.03.004 Haghighi, F., Gorji, M., Shorafa, M., 2010. A study of the effects of land use changes on soil physical properties and organic matter. L. Degrad. Dev. 21, 496–502. https://doi.org/10.1002/ldr.999

Hassink, J. , 1994. Effects of soil texture and grassland management on soil organic C and N and rates of C and N mineralization. Soil Biology and Biochemistry, 26(9), 1221–1231. https://doi.org/10.1016/0038-0717(94)90147-3

Houben, P. (2008). Scale linkage and contingency effects of field-scale and hillslope-scale controls of long-term soil erosion: Anthropogeomorphic sediment flux in agricultural loess watersheds of Southern Germany. Geomorphology, 101(1–2), 172–191. https://doi.org/10.1016/J.GEOMORPH.2008.06.007

Innangi, M., Danise, T., d'Alessandro, F., Curcio, E., Fioretto, A., 2017. Dynamics of organic matter in leaf litter and topsoil within an Italian alder (Alnus cordata (Loisel.) Desf.) ecosystem. Forests 8. https://doi.org/10.3390/f8070240

Kirkby, C.A., Richardson, A.E., Wade, L.J., Batten, G.D., Blanchard, C., Kirkegaard, J.A., 2013. Carbon-nutrient stoichiometry to increase soil carbon sequestration. Soil Biol. Biochem. 60, 77–86. https://doi.org/https://doi.org/10.1016/j.soilbio.2013.01.011

Laganière, J., Angers, D. A., & Paré, D. (2010). Carbon accumulation in agricultural soils after afforestation: A meta-analysis. Global Change Biology, 16(1), 439–453. https://doi.org/10.1111/j.1365-2486.2009.01930.x

Lambin, E. F., Geist, H. J. and Lepers, E. 2003. Dynamics of Land-Use and Land-Cover Change in Tropical Regions. Annual Review of Environment and Resources, 28: 205–241.

Lehmann, J., Kleber, M., 2015. The contentious nature of soil organic matter. Nature 528, 60-68. https://doi.org/10.1038/nature16069

Mayer, M., Prescott, C.E., Abaker, W.E.A., Augusto, L., Cécillon, L., Ferreira, G.W.D., James, J., Jandl, R., Katzensteiner, K., Laclau, J.P., Laganière, J., Nouvellon, Y., Paré, D., Stanturf, J.A., Vanguelova, E.I., Vesterdal, L., 2020. Tamm review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. For. Ecol. Manage. 466, 118127. https://doi.org/https://doi.org/10.1016/j.foreco.2020.118127

Minor, M.A., Cianciolo, J.M., 2007. Diversity of soil mites (Acari: Oribatida, Mesostigmata) along a gradient of land use types in New York. Appl. Soil Ecol. 35, 140–153. https://doi.org/10.1016/J.APSOIL.2006.05.004

Ouyang, W., Xu, Y., Hao, F., Wang, X., Siyang, C., Lin, C., 2013. Effect of long-term agricultural cultivation and land use conversion on soil nutrient contents in the Sanjiang Plain. CATENA 104, 243–250. https://doi.org/https://doi.org/10.1016/j.catena.2012.12.002

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A Large and Persistent Carbon Sink in the World's Forests. Science (80-.). 333, 988 LP – 993. https://doi.org/10.1126/science.1201609

Schneider, D., Engelhaupt, M., Allen, K., Kurniawan, S., Krashevska, V., Heinemann, M., Nacke, H., Wijayanti, M., Meryandini, A., Corre, M.D., Scheu, S., Daniel, R., 2015. Impact of lowland rainforest transformation on diversity and composition of soil prokaryotic communities in Sumatra (Indonesia). Front. Microbiol. 6, 1–12.

Tiessen, H., Cuevas, E., Chacon, P., 1994. The role of soil organic matter in sustaining soil fertility. Nature 371, 783–785. https://doi.org/10.1038/371783a0

Vindušková, O., Pánek, T., Frouz, J., 2019. Soil C, N and P dynamics along a 13 ka chronosequence of landslides under semi-natural temperate forest. Quat. Sci. Rev. 213, 18–29. https://doi.org/10.1016/J.QUASCIREV.2019.04.001

Walker, T.W., Syers, J.K., 1976. The fate of phosphorus during pedogenesis. Geoderma 15, 1–19. https://doi.org/https://doi.org/10.1016/0016-7061(76)90066-5

Wu, J., Zeng, H., Zhao, F., Chen, C., Liu, W., Yang, B., Zhang, W., 2020. Recognizing the role of plant species composition in the modification of soil nutrients and water in rubber agroforestry systems. Sci. Total Environ. 723, 138042. https://doi.org/10.1016/j.scitotenv.2020.138042

Zhang, Z., Wang, J. J., Lyu, X., Jiang, M., Bhadha, J., & Wright, A. (2019). Impacts of land use change on soil organic matter chemistry in the Everglades, Florida - a characterization with pyrolysis-gas chromatography–mass spectrometry. Geoderma, 338, 393–400. https://doi.org/10.1016/J.GEODERMA.2018.12.041

Zheng, S., Xia, Y., Hu, Y., Chen, X., Rui, Y., Gunina, A., He, X., Ge, T., Wu, J., Su, Y., Kuzyakov, Y., 2021. Stoichiometry of carbon, nitrogen and phosphorus in soil: effects of agricultural land use and climate at a continental scale. Soil Tillage Res. 209-104903. https://doi.org/10.1016/j.still.2020.104903

Zucca, C., Canu, A., & Previtali, F. (2010). Soil degradation by land use change in an agropastoral area in Sardinia (Italy). CATENA, 83(1), 46–54. https://doi.org/10.1016/J.CATENA.2010.07.003

CHAPTER 2 - INFLUENCE OF FOREST STAND MANAGEMENT ON SOIL ORGANIC C AND NUTRIENTS (N, P, Ca, Mg, K)

ELSEVIER

Journal of Environmental Management
Volume 312, 15 June 2022, 114935

Research article

Effect of coppice conversion into high forest on soil organic C and nutrients stock in a Turkey oak (*Quercus cerris* L.) forest in Italy

Lorenzo Camponi [a], Valeria Cardelli [a], Stefania Cocco [a], Dominique Serrani [a], Andrea Salvucci [a], Andrea Cutini [b], Alberto Agnelli [c, d], Gianfranco Fabbio [b], Giada Bertini [b], Pier Paolo Roggero [e], Giuseppe Corti [a, f]

Show more

+ Add to Mendeley Share Cite

https://doi.org/10.1016/j.jenvman.2022.114935 Get rights and content

Effect of coppice conversion into high forest on soil organic C and nutrients stock in a Turkey oak (*Quercus cerris* L.) forest in Italy

Lorenzo Camponi[a], Valeria Cardelli[a*], Stefania Cocco[a], Dominique Serrani[a], Andrea Salvucci[a], Andrea Cutini[b], Alberto Agnelli[c,d], Gianfranco Fabbio[b], Giada Bertini[b], Pier Paolo Roggero[e], Giuseppe Corti[a]

[a] Department of Agricultural, Food and Environmental Sciences, Polytechnic University of Marche, Ancona, Italy

[b] CREA-Research Centre for Forestry and Wood, Arezzo, Italy

[c] Department of Agricultural, Food and Environmental Sciences, University of Perugia, Perugia, Italy

[d] Research Institute on Terrestrial Ecosystems (IRET-CNR), Sesto Fiorentino, Italy

[e] Department of Agricultural Sciences, University of Sassari, Sassari, Italy

*****Correspondence: v.cardelli@staff.univpm.it

Abstract

In forest ecosystems, a variety of abiotic and biotic soil forming factors drives soil organic matter (SOM) and nutrients cycling with a profitable outcome on climate change mitigation. As a consequence, type and intensity of forest management, through its impact on carbon (C) and nutrient soil stocks, can be considered as an additional soil forming force. In this study, we investigated the influence of the coppice conversion into high forest on pedogenesis and on soil C and nutrient (N, P, Ca, Mg, and K) stocks, fifty years later the beginning of the conversion-cycle. The trial was established in a Turkey oak forest historically managed under the coppice system in central Italy. Specifically, we considered tree population density (natural evolution – control, moderate thinning, heavy thinning) where soil samples were collected according to genetic horizon to estimate C, N, and P stocks both in the forest floor and at fixed depth intervals (0-30, 30-50 and 50-75 cm). Further, the stocks of exchangeable Ca, Mg, and K were also assessed for the mineral layers. The results showed that litter and the upper layer of mineral soil (0-30 cm) contained a similar quantity of C (about 74-83 $Mgha^{-1}$), independently of the trials and no differences were observed also in the whole soil stocks (about 192-213 Mg ha^{-1}). The comparison of the mean stocks calculated per 1-cm of thickness of organic (O), organo-mineral (OM), and mineral (M) layers, although it did not display any difference among trials (excepted for P and Mg), showed a similar capability of the organo-mineral horizons to store C and nutrients compared with the organic ones (e.g., about 6-12 Mg ha^{-1}, 0.3-0.5 Mg ha^{-1} and 0.5-1.5 kg ha^{-1} for C, N and P, respectively). Our findings showed that thinning operated on Turkey oak coppice did not affect soil capacity to store C and nutrients. These results suggested that the forest ecosystem itself is the main soil forming force and this is consistent with the target of adopting forest management able to control the global C cycle through the storage of SOM in the mineral soil rather than in forest floor, where SOM turnover is faster.

Keywords: forest soil, organic matter, rock fragments, pedogenetic horizons, coppice conversion into high forest, sustainable forest management

1. Introduction

Soil organic matter (SOM) plays key roles in terrestrial ecosystems, where it is involved in many processes of soil conservation. SOM is fundamental in stabilizing soil structures and reducing soil erosion, improving water-holding capacity, and releasing nutrients to plants, microorganisms, and soil fauna (Bot and Benites, 2005; Canedoli et al., 2020). In forest soils, the input of organic matter depends on litter production, mortality of fine roots, roots exudates, and shoots residues (Lehmann et al., 2015; Diao et al., 2020; Wu et al., 2020). Thus, depending on the interaction among the main soil forming forces (parent material, climate, living organisms, relief, and time; Jenny, 1941), a vastity of physicochemical and biological processes affects the transformation of plant-derived organic materials in SOM. During this transformation, SOM is stabilized by the formation of organo-metallic complexes with di- and trivalent cations (Kaiser et al., 2016), the formation of organo-mineral complexes with clay minerals (Kögel-Knabner et al., 2008, Barré et al., 2014; Gartzia-Bengoetxea et al., 2020), and the occlusion within aggregates (Schrumpf et al., 2013), favouring its preservation in the soil. Therefore, plant species, soil properties, and their interactions play a key role in determining the soil organic C (SOC) stock and, due to SOM elemental content, also in the biogeochemical cycles of nutrients like N, P, Ca, Mg, and K (Tiessen et al., 1994). For instance, estimations indicate that the mean world soil content to 1-m depth is 1462-1548 Pg for organic C and 133-140 Pg for total N (Batjes, 1996), more than the global content obtained combining vegetation and atmosphere (Lehmann et al., 2015; Mayer et al., 2020).

In forest ecosystems, forest management may impact on SOC and nutrient stock. In their review, Mayer et al. (2020) reported that management practices like site preparation, harvesting operations, removal of harvest residues, and removal of litter and biomass for fodder, fuel, or animal bedding have a negative impact on SOC stock capacity. Conversely, N addition, introduction of N-fixing plants, and herbivory regulation have a positive impact on SOC storage. Other practices like management of tree species diversity and periodical thinnings over the whole stand lifespan that are used to manage tree population density in high forest [which consists in a stand of trees, generally originated from seed , that develop a high, closed canopy (SAF, 2008)] and in the conversion into high forest of coppice systems seem not to interfere with the soil capacity to stock organic C under both broadleaves and conifers (Bravo-Oviedo et al., 2015; Prasad Dangal et al., 2017; Zhang et al., 2018; Mayer et al., 2020).

Coppicing represents the oldest form of systematic and sustainable use of forests. It is a very flexible system that requires a low energy input and has been adapted and modified according to the needs of rural societies, to whom coppice forests deliver small size wood primarily for energy (firewood and charcoal), agriculture, and small scale businesses. As a matter of fact, coppice forests characterize the European landscapes, especially in mountainous areas of central, east and southern Europe. Due to rural migration and technical and economic restrictions, most of the coppice forests are today neglected or abandoned, representing a significantly underused natural resource (Unrau et al., 2018). In Italy, coppice forests cover 3.663 million hectares (Mairota et al., 2018)) and both evergreen and deciduous *Quercus* spp. make a significant share of the total cover (nearly 1.6 million ha). Following the crisis of the firewood and charcoal system, the conversion of coppices into high-forests is considered a sustainable forest management in many countries (Fabbio, 2016; Fabbio and Cutini, 2017; Cutini et al., 2021) due to the low-frequency soil disturbance that would favour the storage of SOC (Hölscher et al., 2001; Marchi et al., 2016). Therefore, the link between forest management and soil properties, with its specific capacity to determine SOC stock and climate change mitigation, has fostered a number of scientific researches (e.g., Caddeo et al., 2019; Zhang et al., 2019; Zhao et al., 2019; Lee et al., 2020), but scarce has been the interest on the effect of forest management on the soil stock of nutrients like N, P, Ca, Mg, and K, whose abundance and availability is key to soil fertility and biomass production.

The aim of this work was to assess the role of thinning performed for the conversion of a coppice forest into high forest on soil C, N, available P, and exchangeable Ca, Mg, and K stocks. The effect of periodical thinning vs no silvicultural intervention (namely, natural evolution following the suspension of periodical harvestings) was investigated in a Turkey oak (*Quercus cerris* L.) stand under conversion into high forest and managed as coppice up to 1949 (last coppicing).

To test the hypothesis that different forest managements can affect soil C and nutrients stocks, and to investigate on the contribution of each horizon to the whole soil stocks, we estimated: i) C, N, and P stored in the genetic horizons (ranked in organic, organo-mineral and mineral horizons) and at fixed depth intervals (0-30, 30-50, and 50-75 cm); and ii) exchangeable Ca, Mg, and K stored in the mineral soil (organo-mineral and mineral horizons) and at fixed depth intervals (0-30, 30-50, and 50-75 cm).

2. Materials and Methods

2.1. Environmental and historical background

The study was conducted in the Natural Reserve of Monterufoli-Caselli forest, Tuscany, Italy (Fig. 1), a Natura 2000 Site (SPA-SAC IT5170008 Complesso di Monterufoli). The whole reserve covers a gentle hilly environment and extends for 4,828 ha within altitudes spanning between 100 and 560 m. The mean annual precipitation is 750 mm and the mean annual air temperature is 13.5 °C. Geology of the area is rather complex being dominated by serpentinite and polygenic breccias (Paleocene), followed by calcareous sandstone interbedded with limestone (Cretaceous), pelitic marine sediments (Pliocene), silty-clay schists (Cretaceous), and quartzous sandstone interbedded with arenaceous limestone (Paleocene). The area was heavily influenced by human activities since ancient times. Central Italy, and especially Tuscany, was subject to an intense mining activity during Bronze and Iron ages. As reported by Cartocci et al. (2007), Tuscany can be considered one of the most important ancient metallurgical districts of Italy, with several active mining centres since the Iron Age. In the study area, considerable was the production of iron, pyrite, base metals, silver, antimony, mercury, and gold for millennia (Chiarantini et al., 2018). Because of this activity, there was the need of fuel for metal smelting, with the consequent exploitation of forests (especially oak forests of *Quercus cerris* L., *Quercus pubescens* Willd., and others) for charcoal production (Carrari et al., 2017).

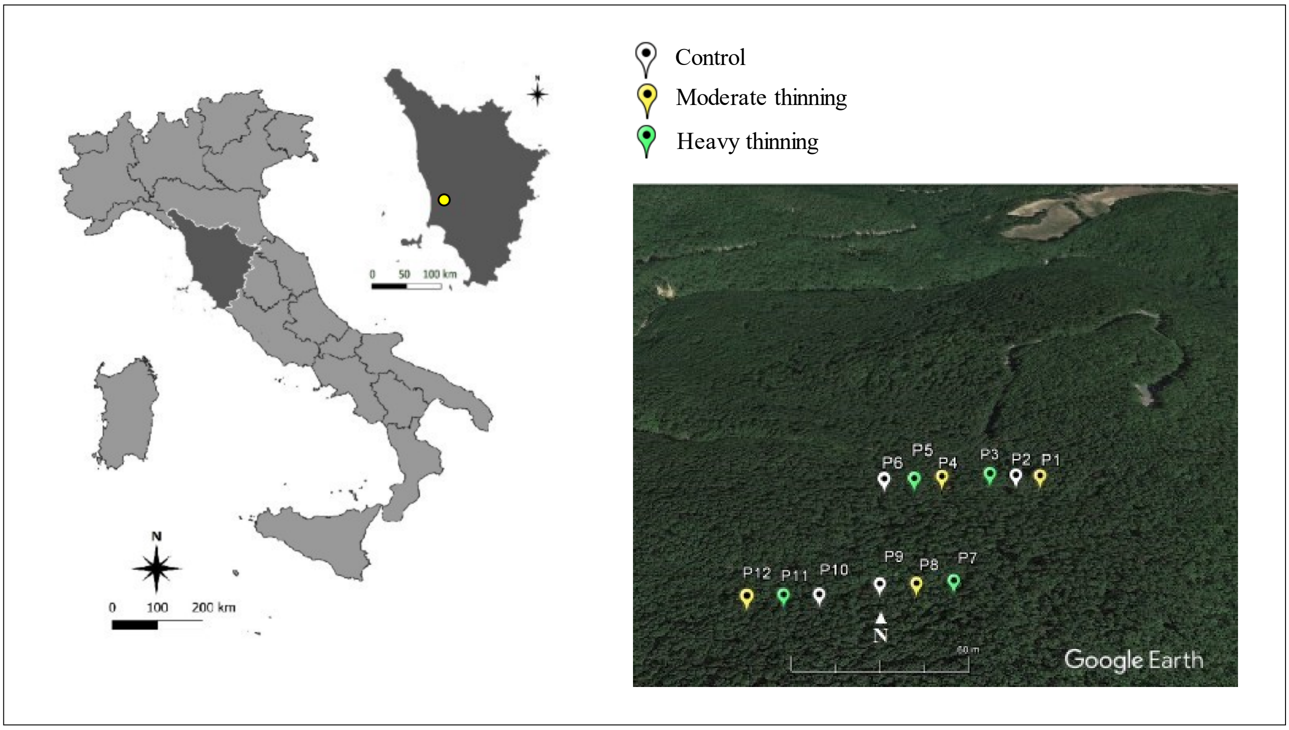


Fig. 1. Study site location in the Natural Reserve of Monterufoli-Caselli forest, Tuscany, Italy, and profiles distribution in the experimental area.

Table 1. Stem density (number per unit area) for the three Turkey oak forest trials (control, moderate thinning and heavy thinning) in the inventory years 1969, 1978, 1989, 1998, and 2004. Natural Reserve of Monterufoli-Caselli forest, Tuscany, Italy.

Trial	Layer	Inventory year						
		1969 (first thinning)		1978	1989 (second thinning)		1998	2004
		Before thinning	After thinning		Before thinning	After thinning		
		No. ha^{-1}						

Control	Total	4269	4191			3589	3653	3417
Heavy thinning	Dominant[a]	n.a.	1093	1089	1037	715	664	578
	Dominated[b]	n.a.	2563	2959	2081	2026	2133	2150
	Total[c]	4988	3656	4048	3118	2741	2797	2728
Moderate thinning	Dominant[a]	n.a.	1500	1481	1292	1036	992	869
	Dominated[b]	n.a.	2466	2542	1783	1764	1811	2183
	Total[c]	5238	3966	4023	3075	2800	2803	3052

n.a.=not available.

[a]Dominant trees constitute the higher canopy level, receiving direct sunlight.

[b]Dominated trees are located under the dominant canopy layer, receiving filtered sunlight.

[c]Total refers to all the trees that constitute the canopy.

2.2. Study area

The study was run in a long-term monitoring area located within the Caselli Forest. Forest stands consisted of Turkey oak (*Quercus cerris* L.) for about 90%, with broadleaves like *Fraxinus* spp., *Ulmus* spp., *Ostrya* spp., and *Quercus ilex* L. as subsidiary species. Under the coppice system, in Italy Turkey oak cover ≈675,000 ha, i.e. the 18.4% of coppice forests (Manetti et al., 2020). Leaf area index (LAI) ranged from 4.3 to 5.2 (Cutini, 1996). Here, last coppicing was performed in 1949; then, in 1969, a long-term experiment aimed at comparing the periodical thinning of standing crop *vs* its natural evolutive pattern to achieve coppice conversion into high forest was established. The main goal of the experiment was to verify stand dynamics as for its structural-compositional arrangement and functional traits of tree biomass. The treatments on the ground were the full release of the dominated layer, moderate thinning (MT) and heavy thinning (HT) with an average release of 1500 and 1100 stems ha^{-1} in the dominant layer, respectively. The coppice under natural evolution, in absence of any practice, was considered as control (CTR); here, the average full tree density was 4269 ha^{-1} (Fabbio and Amorini, 2006; Manetti and Gugliotta, 2006). Each trial was repeated four times according to a randomized blocks design. Within plots of several thousands of m^2, we selected a survey area of 900 m^2 all within a NNE-NNW exposure on slopes roughly ranging from 10 to 20% (Table S1, Supplementary Materials). A second thinning was implemented in 1989 releasing 715 and 1036 shoots ha^{-1} in HT and MT, respectively. Average stem density decreased to 3589 ha^{-1} in CTR. The arrangement of stand structure following the applied silviculture was a two-storied stand: the dominant layer mainly made of Turkey oak, and the dominated layer made the set of subsidiary broadleaved species.

Other inventories were performed in 1998 and 2004. In 2004, there were 578 shoots ha^{-1} in the dominant layer of HT and 869 shoots ha^{-1} in MT. Average full stem density was 3417 ha^{-1} in CTR. Main stand parameters are summarized in Table 1.

2.3. Sampling sites and soil sampling

The study site spanned from 337 to 345 m above sea level, on soil formed on calcareous sandstone interbedded with limestone. In each of the four plots of the three trials, in 2017 a survey was run to evaluate the spatial variability of surface stoniness, rock outcrops, slope, micro-topography, dominant vegetation, and understorey to select the location where to dig a soil profile. Then, a total of 12 profiles (1 profile • 4 plots • 3 trials) representative of each plot conditions were opened within locations with 12-15% slope and 90-95% soil cover. In each plot the soil profile was dug at ≈1 m from the stem (downslope position) of one of the oldest trees and until the depth of ≈1 m, except for lithic contact. For each profile, the organic horizons forming the forest floor were morphologically described per Baize et al. (2008) and sampled in an area of about 3 m^2 around the profile. The mineral soil was morphologically described per Schoeneberger et al. (2012) and sampled by genetic horizons. Soil morphologies provided of understorey composition (Frati et al., 2021) are reported in Table S1 of Supplementary Material. During the field operations, the collected samples were stored in a refrigerated bag and, once in the laboratory, they were allowed to air-dry. Thus, the mineral samples were sieved at 2 mm to separate the fine earth (< 2-mm fraction) from the skeleton (> 2-mm fraction).

2.4. Laboratory analysis

The bulk density of both fine earth and skeleton of each horizon was determined by soil cylinders. Specifically, two horizontal soil cores were collected from each mineral horizon by using cylinders of 503 cm^3 (height: 10.8 cm; diameter: 7.7 cm). In the laboratory, the collected sample was sieved at 2 mm and the volume of the skeletal particles was determined by water displacement after the particles were water-saturated (Corti et al., 1998). The volume of the fine earth was obtained by subtracting that of the skeletal particles from the total volume of the cylinder. Both fine earth and skeleton were then heated at 105°C and weighed. The content of large cobbles was estimated by the "percent of area covered" figure reported in Schoeneberger et al. (2012), and their bulk density determined as mentioned above. For the organic horizons, the bulk density was estimated by pedotransfer functions (De Nicola et al., 2014), which have been tested by other researcher in various Italian contexts (Brenna et al., 2010; Garlato et al., 2009a, b; Guermandi et al., 2013). These equations provide bulk density as a function of the percentage of estimated organic matter (OM = 2 • organic C) as follows:

1. For OM > 30%: bulk density (g cm^{-3}) = 0.00589 • organic C + 0.554;
2. For OM = 30–15%: bulk density (g cm^{-3}) = 0.00745 • organic C + 0.593;
3. For OM < 15%: bulk density (g cm^{-3}) = 0.00797 • organic C + 0.553.

Aliquots of 20 g of fine earth were used to determine the particle-size analysis after they were maintained submerged in deionised water for 24 h; sand was retrieved by wet sieving at 0.053 mm, while silt and clay were obtained by sedimentation. All the following analyses were performed on both fine earth and skeleton. The pH values were determined potentiometrically in water after one night of solid:liquid contact at 1:2.5 w:v ratio for the mineral samples and 1:8 w:v ratio for the organic samples (Cardelli et al., 2019). Total organic carbon (TOC) was estimated by K-dichromate digestion, heating the suspension at 180 °C for 30 minutes (Nelson and Sommers, 1996). Water-extractable organic matter (WEOM) was extracted after one night of the 1:10 solid:liquid suspension in an orbital shaker at 140 rpm and filtered through a Whatman 42 filters (Agnelli et al., 2014). The organic C content of the extract (WEOC, water-extractable organic carbon) was determined by titration (Nelson and Sommers, 1996). Total N (TN) was measured by a dry combustion analyser (EA-1110, Carlo Erba Instruments, Milan, Italy), while available P (P_{av}) was determined following the Olsen et al. (1954) method. Exchangeable Ca, Mg, and K were displaced by a 0.2 M $BaCl_2$ solution (solid:liquid ratio 1:10) and extracted after 10 min of shaking (Corti et al., 1997). The obtained suspensions were centrifuged and filtered through Whatman 42 filters. Elements were determined by atomic absorption with a Shimadzu AA-6300 spectrophotometer (Tokyo, Japan). For the skeletal fraction, pH, P_{av}, and exchangeable Ca, Mg, and K were determined on unground fragments, while TOC, WEOC, and TN were measured on ground aliquots (Ugolini et al. 1996; Corti et al., 1997; Corti et al., 2002).

2.5. Stock calculation

Soil rock fragments can contain considerable amounts of nutrients (Ugolini et al., 1996). In particular, as pointed out by Corti et al. (2002) and Cuniglio et al. (2009), calcareous skeleton may represent a large reservoir of C, N, and nutrient cations. Thus, considering the soil as made of fine earth only may result in significant overestimations of the soil nutrient budget. Therefore, C and nutrients (N, P, Ca, Mg, K) stocks were calculated for each genetic horizon taking into consideration both fine earth and skeleton contributions.

The amount of element stored in the fine earth and skeleton was calculated as following (De Nicola et al., 2014):

$$ES = EC \bullet BD \bullet TH \bullet CC \quad (1)$$

where ES is the element stock (in Mg ha^{-1} for C, N, and exchangeable Ca, Mg, and K; in kg ha^{-1} for P_{av}), EC is the element concentration (g kg^{-1} for C and N; mg kg^{-1} for P_{av} and exchangeable Ca, Mg, and K), BD is the bulk density (kg dm^{-3}), TH is the horizon thickness (cm), and CC is the coefficient applied to normalize the units of measure (10^{-1} for C, N and Pav; 10^{-4} for exchangeable Ca, Mg, and K).

Thus, the total C and nutrient stored in each genetic horizon were determined as the weighed mean for the fine earth and skeleton contents:

$$ESTOT = [(ESfe \bullet FE\%) + (ESsk \bullet SK\%)] / 100 \quad (2)$$

where ES_{TOT} is the total amount of element stored in the genetic horizon (in Mg ha^{-1} for C, N, and exchangeable Ca, Mg, and K; in kg ha^{-1} for P_{av}), ES_{fe} is the amount of element contained in the fine earth, FE% is the percentage of fine earth content in the horizon, ES_{sk} is the amount of element contained in the skeleton, SK% is the percentage of skeleton content in the horizon.

For each element, the amount stored by 1-cm thickness of the organic, organo-mineral, and mineral horizons was also calculated.

2.6. Statistical analysis

Because of the soil variability, profiles showed slight differences in the sequence of horizons. Thus, genetic horizons were grouped into soil layers based on their nature: forest floor (OLn, OLv, OFr, and OH horizons), organo-mineral (A and AB horizons), and mineral (Bw, Bg, BC, and Cr horizons). Properties of the soil layers were obtained by calculating the weighed mean of each property based upon the thickness of each horizon. The element stocks for the 0-30, 30-50, and 50-75 cm of soil were calculated considering the thicknesses of the organo-mineral and mineral soil horizons. To highlight differences in C and nutrient stocks, one-way ANOVA was performed along the soil layers and among soils under different forest managements. Prior to ANOVA, normality and homoscedasticity of the dataset were assessed using Shapiro-Wilk statistical test and by Levene's test at 5% significance level, respectively. Assumptions were not violated and Tukey's Honest Significant Difference (HSD) test with $P \leq 0.05$ was used to compare differences among means. Results of ANOVA (*F value* and *significance level*), showing the influence of management and depth on physical and chemical properties and elements stock in the surveyed soils are reported in Table S5 a/b of Supplementary Materials.

3. Results

3.1. Soil morphology, and physical and chemical properties in the three forest trials

Properties of the experimental site were similar in the three forest trials.

All the soils were classified as Humustepts (Soil Survey Staff, 2014). Soil morphology organized in soil layers is reported in Table 2 and Table S1 of Supplementary Material. The litter layer was on average 2 to 5 cm thick and was mainly made by Turkey oak leaves and branch fragments. Organo-minerals horizons showed a thickness spanning from 2 to 6 cm thick, and the soil structure was moderately to well-developed, in form of crumbs or subangular blocks; in the area massively frequented by wild boars (MT), the structure was platy. Mineral horizons showed poorly to well-developed structure mainly made of subangular and angular blocks. Gley B horizons (Bg) indicate periodical soil water saturation (Soil Survey Staff, 2014). The skeleton content in the three trials ranged from 0 to 50-60%, with the greatest contents in depth (Table 2). The soil pH was sub-acid (ranging between 5.69 and 6.15), with no significant difference among layers and trials (Table 3). The particle-size distribution showed a coarser texture in the organo-mineral horizons (loam to sandy-loam textures) than in the mineral ones (silty clay and clay loam). No statistically significant difference ($P > 0.05$) among the trials was observed. As expected, the largest contents of TOC, WEOC, TN, and P_{av} were in the litter and showed a decreasing trend with depth. Among the trials, no difference occurred for TOC, WEOC, and TN, whereas the organo-mineral horizons of HT displayed the highest P_{av} concentrations. The WEOC/TOC ratio showed very high values with respect to other reports (Corvasce et al., 2006; De Feudis et al., 2017), with statistically significant differences only in the MT trial, where the mineral horizons displayed the highest value. The C/N ratio showed a significantly decreasing trend with depth in all the trials, with no significant difference among them (Table 3, S2 and S3 of Supplementary Material for fine earth and skeleton data, respectively).

Table 2. Average morphological properties of the soil profiles under *Quercus cerris* L. in the three forest trials (Heavy thinning, Moderate thinning, and Control), according to each soil layer category. Natural Reserve of Monterufoli-Caselli forest, Tuscany, Italy. For symbols see legend.

Trial	Mean slope	Exposure	Layer	Horizons[a]	Depth[b]	Thickness[c]	Boundary[d]	Colour[e]	Structure[f]	Consistence[g]	Roots[h]	Skeleton[i]	Observation
	%	From - to			cm							%	
Heavy thinning	15-25	NNW W	Litter	OLn; OLv; OH	4/3-0	1.5-3.5	cw cb ab	- 5YR 3/2	-	-	0	40-60	Undecomposed leaves and little branches
			Organo-mineral	A; AB	0-5/4	2-5	cw aw	5YR 3/1 7.5YR 2.4/2	3f gr 1-3f,m gr+sbk	fr fi	2mi,vf,f,m 3mi,vf,f,m, co	40-60	Mycelium
			Mineral	BA; BC, C	3/5-35/65	11-15	cw sw	5YR 4/6 10YR 7/3	1m abk, 2f,m sbk 3f,m sbk,abk	fr	1mi,vf,f,m, co 2mi,vf,f; 3m,co	<1-50	Cutans
Moderate thinning	12-18	NNW NNE	Litter	OLn; OLv; OFr; OH	10/6-0	2-4	cw cs	- 7.5YR 3/2	-	-	0 2mi,vf,f	5-30	Intense wild boar turbation. Leaves and branch fragments. Mesofauna
			Organo-mineral	A; AB	0-2/17	3-6	aw cw	7.5YR 2.5/1 10YR 4/3	2f,m,cr pl→m abk 3f,m,c cr,abk,sbk	fr	1mi,vf 2mi,vf; 3f,m,co	0-30	Intense wild boar turbation. Charcoal fragments
			Mineral	Bw, Bg	2/17-87/130	17-21	cw	7.5YR 3/1 10YR 7/3 5YR 4/6	1m,abk,sbk 2-3f,m abk,sbk	fr	1mi,vf,m,co 2-3mi,vf,f,m, co	0-30	Charcoal fragments. Mycelium. Cutans
Control	11-16	NNW NNE	Litter	OLn; OLv; OFr; OH	10/7-0	2-5	cw as	7.5YR 3/2	-	-	0 1mi,vf,f	0-20	Leaves and branch fragments. Mesofauna. Mycelium
			Organo-mineral	A; AB	0-2/8	3-5	cw	7.5YR 2.5/1 10YR 4/4	2f,m sbk 3f cr	fr	2mi,vf,f 3mi,vf,f; 1m	0-10	Charcoal fragments. Mycelium
			Mineral	Bw, Bg, BC	2/8-56/155	23-27	cw cs	10YR 4/3 10YR 6/4	2f,m,c abk,sbk 3f,m sbk,abk	fr	1mi,vf,f,m, co 2mi,vf; 3f,m,co	0-60	Charcoal fragments. Mycelium. Cutans

[a] designation according to Baize et al. (2008) for organic horizons, to Schoeneberger et al. (2012) for mineral horizons.
[b] Numbers separated by slash (/) indicate the range of depths observed in the four profiles, while the hyphen (-) means "from (what is before it) to (what is after it)".
[c] referred to the lowest and highest mean thickness.
[d] a=abrupt, c=clear; g=gradual; d=diffuse; s=smooth; w=weavy; i=irregular; b=broken
[e] moist and crushed, according to the Munsell Soil Color Charts. The reported colors are the extremes for the horizons considered.
[f] 1=weak, 2=moderate, 3=strong; th=thin, f=fine, m=medium, c=coarse; cr=crumb, abk=angular blocky, sbk=sub-angular blocky, pl=platy. The reported structures are the extremes for the horizons considered.
[g] fr, friable.
[h] 0=absent, v_1=very few, 1=few, 2=plentiful, 3=abundant; mi=micro, vf=very fine, f=fine, m=medium, co=coarse. The reported roots abundances are the extremes for the horizons considered.
[i] The reported values are the extremes for the horizons considered.

Table 3. Mean values of pH, particle-size distribution, concentration of total organic carbon (TOC), water-extractable organic C (WEOC), total nitrogen (TN), and available phosphorus (P_{av}), and WEOC/TOC and C/N ratios of the soil layers under Turkey oak forest submitted to three management trials (control, moderate thinning and heavy thinning). Natural Reserve of Monterufoli-Caselli forest, Tuscany, Italy. Numbers in parentheses are the standard deviations. Columns with different lowercase letters indicate differences within each trial, columns with different capital letters indicate differences within the same soil layer among trials, both at $P \leq 0.05$ level of significance.

Trial	Soil horizons	n	pH	Particle-size distribution			TOC	WEOC	TN	P_{av}	WEOC/TOC	C/N
				Sand	Silt	Clay						
				g kg^{-1}			g kg^{-1}			mg kg^{-1}		
Control	Litter	7	5.96 ^{aA} (0.64)	-	-	-	362.44 ^{aA} (103.06)	7.91 ^{aA} (3.57)	13.54 ^{aA} (1.66)	36.6 ^{aA} (9.9)	0.02 ^{aA} (0.00)	26.6 ^{aA} (2.7)
	Organo-mineral	5	5.89 ^{aA} (0.71)	467 ^{aA} (110)	387 ^{aA} (56)	146 ^{bA} (56)	99.93 ^{bA} (46.53)	2.23 ^{bA} (0.48)	5.33 ^{bA} (2.24)	4.8 ^{bB} (4.6)	0.02 ^{aA} (0.00)	18.6 ^{bA} (2.6)
	Mineral	10	5.86 ^{aA} (1.05)	155 ^{bA} (63)	373 ^{aA} (23)	472 ^{aA} (68)	13.64 ^{cA} (3.15)	0.59 ^{bA} (0.17)	0.94 ^{bA} (0.09)	1.6 ^{bA} (1.7)	0.05 ^{aA} (0.02)	11.3 ^{cA} (5.9)
Moderate thinning	Litter	9	5.91 ^{aA} (0.54)	-	-	-	316.40 ^{aA} (99.97)	6.63 ^{aA} (2.92)	12.51 ^{aA} (1.52)	36.0 ^{aA} (11.9)	0.02 ^{bA} (0.01)	25.3 ^{aA} (1.3)
	Organo-mineral	4	5.69 ^{aA} (0.74)	330 ^{aA} (166)	443 ^{aA} (85)	227 ^{bA} (82)	57.00 ^{bA} (61.64)	1.19 ^{bA} (1.52)	3.32 ^{bA} (3.15)	6.7 ^{bB} (4.8)	0.02 ^{bA} (0.01)	17.1 ^{bA} (5.0)
	Mineral	9	5.99 ^{aA} (0.94)	143 ^{bA} (52)	399 ^{bA} (44)	459 ^{aA} (84)	9.57 ^{cA} (3.94)	0.64 ^{bA} (0.29)	1.04 ^{cA} (0.54)	0.8 ^{cA} (0.9)	0.07 ^{aA} (0.03)	10.6 ^{bA} (3.3)
Heavy thinning	Litter	8	6.02 ^{aA} (0.60)	-	-	-	312.59 ^{aA} (102.18)	7.04 ^{aA} (2.90)	12.02 ^{aA} (1.74)	34.8 ^{aA} (9.1)	0.02 ^{aA} (0.00)	25.3 ^{aA} (0.5)
	Organo-mineral	6	6.15 ^{aA} (0.11)	627 ^{aA} (96)	269 ^{bA} (63)	104 ^{bA} (398)	145.27 ^{bA} (39.29)	2.12 ^{bA} (0.50)	6.27 ^{bA} (2.06)	19.0 ^{bA} (4.9)	0.01 ^{aA} (0.01)	23.5 ^{aA} (6.8)
	Mineral	11	5.75 ^{aA} (0.59)	184 ^{bA} (99)	378 ^{aA} (57)	438 ^{aA} (110)	11.88 ^{cA} (6.38)	0.50 ^{bA} (0.21)	1.11 ^{cA} (0.43)	1.3 ^{cA} (1.7)	0.05 ^{aA} (0.03)	10.6 ^{bA} (0.4)

3.2. C and nutrient stocks in the three forest trials

In the three trials, litter and the upper 0-30 cm mineral layer contained similar quantity of C, which was higher than in the 30-50 and 50-75 cm mineral layers (Table 4). Other differences among litter and mineral layers were observed for TN in CTR, exchangeable Ca in HT, and K in HT and MT, always with the highest stock in the 0-30 cm layer. However, the stock of all elements showed no statistical difference among the trials. The contribution of the skeleton to the element stocks was negligible or null for C, TN, and P_{av}, but ranged from ≈1.5 to ≈11% for exchangeable K, and from ≈27 to ≈63% for exchangeable Ca and Mg (Table 4 and Table S4 of Supplementary Material).

The amount of the elements stored by 1-cm thickness of the organic, organo-mineral, and mineral horizons in the three trials is reported in Fig. 2. The quantity of C, TN, and P_{av} stored in 1 cm of litter was often similar to that of the organo-mineral horizons (except for P_{av} in CTR), and from three- to ten-fold higher than that of the mineral horizons (except for TN in CTR, where no significant difference was observed). For the exchangeable Ca, Mg, and K, the stock capacity of 1 cm of organo-mineral horizons was generally greater than in the mineral horizons but because the samples were small (Webster, 2001), the differences were not statistically significant except for Ca in MT, Mg in HT, and K in both HT and MT, where the variability was proportionally less than in the other cases. Contrasting the stock capacity per 1-cm thickness among the different trials, only P_{av} and exchangeable Mg showed significant differences, with the highest contents of the two elements in the organo-mineral horizons of HT (Table 3).

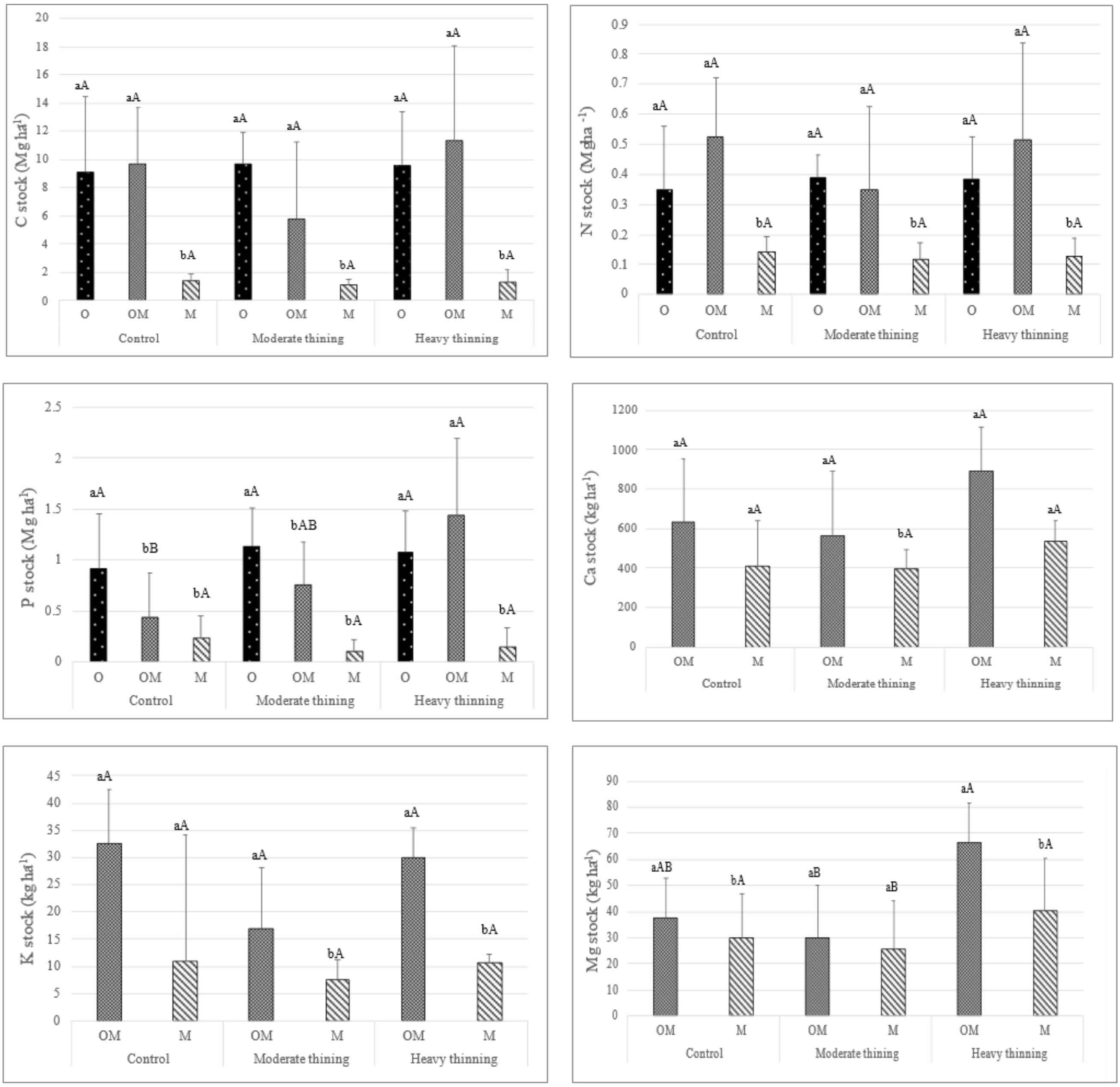


Fig. 2. Stocks of C and nutrients per 1-cm thickness of organic (O), organo-mineral (OM), and mineral (M) layers in the soils under Turkey oak forest submitted to three management trials (control, moderate thinning and heavy thinning). Natural Reserve of Monterufoli-Caselli forest, Tuscany, Italy. Whiskers are the standard deviations. Different lowercase letters indicate differences among soil layers for each property within trial, different capital letters indicate differences within the same soil layer among trials, both at *P*≤0.05 level of significance.

4. Discussion

4.1. Effect of thinning on soil morphology and physicochemical properties

The effect of thinning on the main pedological features appeared negligible in the studied forest. In the topsoil, which is the soil portion most sensitive to disturbances and management practices (Song et al., 2005), the effect of thinning could have been masked by the wild boar activity. In our case, the topsoil mixing due to wild boars seemed to have not substantially affected the soil morphology, probably because all trials have been characterized over time by their presence, albeit with different intensities.

Although the soils developed from calcareous parent material, the soil profiles displayed sub-acid pH values, indicating that soils have been subjected to a heavy decarbonation induced by several acidification processes (Haynes, 1990; Richter et al., 2007; Lemanceau et al., 2009; Chapin et al., 2011; Cocco et al., 2013; Corti et al., 2019). Because of this, and the long time needed to dissolve all carbonates (Cocco et al., 2013), these soils can be considered as highly weathered (e.g., Sundquist and Visser, 2003) and, consequently, it was not expected that the forest thinning could induce marked changes on soil pH in 50 years. Moreover, even when carbonates have been dissolved, acidification is buffered by clay and organic matter (Brady and Weil, 2017), which contribute to reduce pH changes. The soil texture is a parameter not responding quickly to environmental changes; in fact, it is similar for all the trials. Along the profiles, the texture was finer at depth than at the surface probably for the occurrence of lessivage, a process that requires long time to produce differences in terms of soil texture and drainage (Buurman et al., 1998; Quénard et al., 2011; Calabrese et al., 2018).

The decreasing of TOC, TN, and P_{av} with depth is a common trend in soil and especially in forest soils, where the majority of the biomass produced is added in form of litter (Mason and Zanner, 2005). While TOC and TN were not affected by thinning, as they respond slowly to changes (Bai et al., 2017), the different P_{av} content in the organo-mineral and mineral horizons of the three trials were considered an effect of the forest thinning. In fact, working on soils under *Fagus sylvatica* forests, Cardelli et al. (2019) reported that P liberation and activity of enzymes involved in the P cycle are higher in the organo-mineral (A) than in the organic (O) horizons because of the major content of decaying SOM and the consequently greater availability of P-bearing substances like nucleic acids, carbohydrates, proteins, and fatty acids. The major reduction of the canopy density in HT might have enhanced SOM degradation through the increased solar radiation and temperature (e.g., Gressel et al., 1996; Scharenbroch and Bockeim, 2007; Cheng et al., 2021)), with the subsequent higher release of P.

The WEOM content and the WEOM/TOC ratio did not change among the trials. This behaviour was unexpected because WEOM, which is composed of easily degradable molecules that represent the main C and energy source for the soil microbial community (De Feudis et al., 2019), is considered as an indicator of microbial activity (Gutiérrez-Girón et al., 2015), very sensitive to disturbances and management (Chantigny, 2003). However, since the WEOM is released following SOM mineralization (Bartos et al., 2020) and the two thinning intensities did not produce different litter thicknesses (Table 2) and soil TOC and TN concentrations (Table 3) in respect to the control, it would justify the similar WEOC contents and WEOC/TOC ratios found among the trials. Throughout the profiles, the decreasing content of WEOC and the parallel increase of WEOC/TOC ratio (statistically significant only in MT) confirmed the importance of this soluble fraction as energetic substrate for the organisms harbouring the deeper soil horizons. The increase of the WEOC/TOC ratio in the mineral layers, where the clay content is the highest, could be also due to adsorption of organics on the clay mineral lattices, with the formation of mobile organo-mineral complexes (Corvasce et al., 2006).

The magnitude of the values of the C/N ratio for the three trials agreed with those reported in other studies conducted on Mediterranean forests (Corral-Fernández et al., 2013; Cools et al., 2014). The decreasing trend of the C/N ratio with depth is a common trend in forest soils, where the litter is made by less degraded (and with higher C/N ratio) biomass than the organic molecules translocated into the deeper soil horizons after SOM decaying (Marinari et al., 2021).

Table 4. Stocks of C, total N (TN), available P (P_{av}), and exchangeable Ca, Mg, and K, and relative contribution of the fine earth (FE), for the soil thicknesses 0-30 cm, 30-50 cm, and 50-75 cm under Turkey oak forest submitted to three management trials (control, moderate thinning and heavy thinning). Natural Reserve of Monterufoli-Caselli forest. Numbers in parentheses are the standard deviations. Different lowercase letters indicate differences among soil layers for each property within trial, different capital letters indicate differences within the same soil layer among trials, both at P≤0.05 level of significance.

Stock	Thickness	Control		Moderate thinning		Heavy thinning	
		Total stock	FE (%)	Total stock	FE (%)	Total stock	FE (%)
C stock (Mg ha^{-1})	Litter	79.81^{aA} (9.58)	99.99	74.86^{aA} (31.67)	99.99	74.38^{aA} (11.33)	99.99
	0-30 cm	82.78^{aA} (16.64)	99.99	75.86^{aA} (11.92)	99.99	75.71^{aA} (28.19)	99.99
	30-50 cm	23.06^{bA} (9.17)	99.99	20.77^{bA} (4.70)	99.99	23.72^{bA} (11.65)	99.99
	50-75 cm	27.07^{bA} (11.93)	99.99	20.52^{bA} (3.08)	99.99	28.42^{bA} (14.91)	99.99
TN stock (Mg ha^{-1})	Litter	3.04^{bA} (0.47)	99.99	3.00^{aA} (1.15)	99.99	2.97^{aA} (0.46)	99.99
	0-30 cm	6.07^{aA}	99.99	5.10^{aA}	99.99	5.46^{aA}	99.99

		(1.10)		(1.18)		(2.45)	
	30-50 cm	2.40^{bA} (0.80)	99.99	2.39^{aA} (1.43)	99.99	2.70^{aA} (1.40)	99.99
	50-75 cm	2.89^{bA} (1.22)	99.99	3.40^{aA} (0.52)	99.99	3.21^{aA} (1.80)	99.99
P_{av} stock (kg ha^{-1})	Litter	8.06^{aA} (1.30)	100.00	8.78^{aA} (4.94)	100.00	8.37^{aA} (1.35)	100.00
	0-30 cm	8.93^{aA} (6.00)	100.00	8.25^{aA} (6.61)	100.00	8.48^{aA} (4.63)	100.00
	30-50 cm	2.45^{aA} (3.10)	100.00	1.60^{aA} (2.86)	100.00	2.46^{aA} (3.10)	100.00
	50-75 cm	3.06^{aA} (3.87)	100.00	1.94^{aA} (2.18)	100.00	2.12^{aA} (4.07)	100.00
Exchangeable Ca stock (Mg ha^{-1})	0-30 cm	11.13^{aA} (3.30)	85.05	10.70^{aA} (7.55)	80.37	16.98^{aA} (1.83)	73.57
	30-50 cm	11.11^{aA} (4.62)	62.69	8.74^{aA} (4.57)	80.27	11.27^{bA} (1.38)	69.62
	50-75 cm	9.28^{aA}	63.18	11.09^{aA}	79.54	14.05^{abA}	69.45

		(7.63)		(1.80)		(5.79)	
Exchangeable Mg stock (Mg ha^{-1})	0-30 cm	0.77^{aA} (0.10)	73.37	0.74^{aA} (0.35)	67.67	1.23^{aA} (0.60)	55.75
	30-50 cm	0.76^{aA} (0.44)	37.49	0.48^{aA} (0.21)	59.10	0.73^{aA} (0.48)	45.62
	50-75 cm	0.63^{aA} (0.60)	37.99	0.48^{aA} (0.42)	54.30	0.89^{aA} (0.62)	43.41
Exchangeable K stock (Mg ha^{-1})	0-30 cm	0.53^{aA} (0.47)	98.35	0.29^{aA} (0.04)	96.58	0.40^{aA} (0.12)	94.87
	30-50 cm	0.17^{aA} (0.06)	88.82	0.15^{bA} (0.04)	94.72	0.19^{bA} (0.07)	91.76
	50-75 cm	0.14^{aA} (0.13)	88.60	0.16^{bA} (0.06)	93.48	0.23^{abA} (0.07)	91.22

4.2. Effect of thinning on the stocks of C and nutrients

In all the trials, SOC stock is similar in both litter (with a general thickness of 6-10 cm) and 0-30 cm layer, while the SOC stored below 30 cm depth amounted to 54-69% of that in the upper layer. The large amount of C stored in the sub-superficial mineral soil has a basic ecological relevance due to the role of forest soils as C sink and, hence, in the climate change mitigation. In the mineral layers, SOM is stabilized and protected from degradation (e.g., Ono et al., 2013; Yao et al., 2019) mostly because of clay minerals associations and oxygen limitation (e.g., Wattel-Koekkoek et al., 2003; Kleber, 2010). As a consequence, with increasing depth the C turnover rate slows down and the mean residence time of SOM (e.g., Trumbore, 2000; Wang and Chang, 2001) and decaying roots (e.g., Agnelli et al., 2014) tend to increase.

Regarding the different stocks observed along the depth for TN (in CTR) and exchangeable Ca (in HT) and K (in HT and MT), they appeared not related with the amount of roots or with the presence of leguminous species in the understorey that could have enriched the soil of N (Table S1 of Supplementary Materials). The knowledge on the influence of thinning on the stock of elements in the different layers along the soil depth is scarce but, working on a multi-centennial holm oak (*Quercus ilex* L.) forest in a pedoclimatic condition similar to that of our trials, Agnelli et al. (2016) found that many soil features, especially those not directly linked to the microbial activity, were rather homogeneous for each soil depth because of the long lasting pedogenesis. Since our trials were established under a forest cover as old as at least three millennia, we believe that, especially for exchangeable Ca and K, differences derived from spatial differences of parent material and skeleton content rather than to thinning experimentation started ≈50 years before this study.

The three trials showed no significant effect for none of the four (in case of C, N, and P_{av} stocks) or three (for exchangeable Ca, Mg, and K) layers considered. Thinning has been reported not to be able to produce changes on the organic C (and N) stock in naturally settled broadleaves and conifers stands (e.g., Bravo-Oviedo et al., 2015; Bai et al., 2017; Prasad Dangal et al., 2017; Zhang et al., 2018; Mayer et al., 2020). Opposite results were found in planted forests. For example, in their review Gong et al. (2021) took into consideration 77 articles on the effect of forest thinning on SOC stocks in the 0–30 cm mineral soil thickness across planted forests in China and concluded that a moderate thinning significantly increased SOC stocks with respect to both no-thinning and heavy thinning. Instead, working in a *Picea crassifolia* Kom. plantations, He et al. (2018) observed a decrease of the C stock with increasing thinning intensity, with a parallel increase of soil water storage. These reports reinforced the hypothesis that thinning cannot affect the stock of C and other elements in soils with long forest cover history, where pedogenesis has heavily homogenized the soil profile.

The 1-cm stock values confirmed that the organic and the organo-mineral horizons are able to stock similar amounts of C, TN, and P_{av}, while more in depth this ability is minor. While the concentration of C and TN in the organic and organo-mineral horizons was ascribed to their richness of SOM, the large concentration of P_{av} was attributed to the degradation of SOM, which released P from the organic structures (e.g., Pistocchi et al., 2018; Ni et al., 2021). With respect to 1 cm of mineral horizons, the ability of 1 cm of organo-mineral horizons to stock nutrient cations was statistically significant only for Ca in MT, Mg in HT, and K in HT and MT, but a generalized trend was observed in all cases, even though the differences were not significant because the samples were relatively small. In all these cases, the differences were attributed to the relatively fast SOM degradation occurring in the organo-mineral horizons (e.g., Pistocchi et al., 2018; Wang et al., 2019).

When contrasting the 1-cm stock capacity among the trials, thinning appeared to have an effect only on P_{av} and exchangeable Mg, which assumed the highest values in the organo-mineral horizons of HT. Also in this case, although not significant, the same appeared true at least for the potentially available Ca, while for the exchangeable K differences were probably disturbed by spatial variability of parent material and skeleton contribution. However, since a more intense thinning is expected to induce a diffuse higher soil water storage because of the resulted lower canopy density (He et al., 2018), it is probable that a larger water availability in the organic and organo-mineral horizons favoured a greater SOM mineralization with consequent release of nutrients (e.g., Vesterdal et al., 1995; Prescott, 2002; Chiti et al., 2015; Gross et al., 2018).

5. Conclusions

The soil physicochemical parameters and the stock of C and nutrients in the litter and in the 0-30, 30-50, and 50-75 cm layers under a multi-millennial Turkey oak forest cover, appeared slightly influenced by thinnings operated along the last 50 years. This result, which contradicts our research hypothesis, was achieved considering the contribution of the skeletal fraction that, especially in depth, was present in a considerable amount. The only parameters that appeared to be more affected by thinning were P_{av} and exchangeable Mg. The more intense thinning was able to increase the 1-cm storage of the organo-mineral horizons via a major SOM mineralization. Our results contrast with those reported for recently (decades) planted forests, especially if plantation occurs in former cultivated fields, where thinning has tangible effects on element storage. This is equivalent to saying that, after about three millennia of Turkey oak forest use, both forest cover and human activity are the main soil forming forces.

Our study also showed that organo-mineral and mineral horizons under the Turkey oak forest are able to store an amount of SOM similar to the litter layers. Since the SOM contained into the organo-mineral and mineral horizons has higher recalcitrance and, consequently, is less involved in the C turnover processes than that of the forest floor, it is mandatory to adopt forest managements strategies able to increase SOM in depth rather than in the superficial organic horizons, to affect positively the global C cycle.

Finally, considering that *i*) coppice stands under conversion into high forest via natural evolution and by means of periodical thinnings appeared to be equal as for soil ecosystem properties 50 years later, and that *ii*) the latter option is more profitable for environmental, socio-economic issues and recreational purposes, thinning implementation can be considered as a valuable solution, among the different and complementary strategies on the floor, to manage nowadays the original coppice area.

Acknowledgements

We are indebted to Leonardo Tonveronachi for his help during the field activities.

Funding: This work was supported by European project FutureForCoppices LIFE14 ENV/IT/000514.

References

Agnelli, A., Massaccesi, L., De Feudis, M., Cocco, S., Courchesne, F., Corti, G., 2016. Holm oak (*Quercus ilex* L.) rhizosphere affects limestone-derived soil under a multi-centennial forest. Plant and soil. 400, 297-314. https://doi.org/10.1007/s11104-015-2732-x

Agnelli, A., Bol, R., Trumbore, S.E., Dixon, L., Cocco, S., Corti, G., 2014. Carbon and nitrogen in soil and vine roots in harrowed and grass-covered vineyards. Agric. Ecosyst. Environ. 193, 70–82. https://doi.org/10.1016/j.agee.2014.04.023

Bai, S.H., Dempsey, R., Reverchon, F., Blumfield, T. J., Ryan, S., Cernusak, L. A., 2017. Effects of forest thinning on soil-plant carbon and nitrogen dynamics. Plant Soil 411, 437–449. https://doi.org/10.1007/s11104-016-3052-5

Baize, D., Girard, M.C., 2008. Référentiel Pedologique, Edition Quæ. Association francaise pour l'etude du sol (Afes), Versailles, France.

Barré, P., Fernandez-Ugalde, O., Virto, I., Velde, B., Chenu, C., 2014. Impact of phyllosilicate mineralogy on organic carbon stabilization in soils: Incomplete knowledge and exciting prospects. Geoderma 235–236, 382–395. https://doi.org/10.1016/j.geoderma.2014.07.029

Bartos, A., Szymański, W., Klimek, M., 2020. Impact of conventional agriculture on the concentration and quality of water-extractable organic matter (WEOM) in the surface horizons of Retisols—A case study from the Carpathian Foothills in Poland. Soil and Tillage Research, 204. https://doi.org/10.1016/j.still.2020.104750.

Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. Eur. J. Soil Sci.

https://doi.org/10.1111/ejss.12114_2

Bot, A., Benites, J., 2005. The Importance of Soil Organic Matter: Key to Drought-resistant Soil and Sustained Food Production, ed. Food and Agriculture Organization of the United Nation (FAO), Rome.

Brady, N.C., Weil, R.R., 2017. The Nature and Properties of Soils. Fifteenth ed. Upper Saddle River, New Jork. https://doi.org/10.2136/sssaj2016.0005br

Bravo-Oviedo, A., Ruiz-Peinado, R., Modrego, P., Alonso, R., Montero, G., 2015. Forest thinning impact on carbon stock and soil condition in Southern European populations of *P. sylvestris* L. For. Ecol. Manag. 357, 259–267. https://doi.org/10.1016/j.foreco.2015.08.005

Brenna, S., Rocca, A., Sciaccaluga, M., Valagussa, M., 2010. Sistema di Monitoraggio della Qualità dei Suoli di Lombardia, Sperimentazione condotta nell'ambito del progetto di ricerca n. 1032 "Sistema di monitoraggio della qualità dei suoli di Lombardia". "Foto a cura di: Marco Sciaccaluga, Alberto Rocca. - SOILQUALIMON" (d.g.r. 22 marzo 2006 n. VIII/2182 – Programma di attività 2006). Quaderni della Ricerca n. 110 - maggio 2010. Regione Lombardia - Direzione Generale Agricoltura U.O. – Ente regionale per i servizi all'agricoltura e alle foreste.

Buurman, P., Jongmans, A.G., PiPujol, M.D., 1998. Clay illuviation and mechanical clay infiltration — Is there a difference? Quat. Int. 51–52, 66–69. https://doi.org/10.1016/S1040-6182(98)90225-7

Caddeo, A., Marras, S., Sallustio, L., Spano, D., Sirca, C., 2019. Soil organic carbon in Italian forests and agroecosystems: Estimating current stock and future changes with a spatial modelling approach. Agric. For. Meteorol. 278, 107654. https://doi.org/10.1016/J.AGRFORMET.2019.107654

Calabrese, S., Richter, D. D., & Porporato, A. M.,2018. The formation of clay-enriched horizons by lessivage. Geophysical Research Letters, 45, 7588– 7595. https://doi.org/10.1029/2018GL078778

Canedoli, C., Ferrè, C., Abu El Khair, D., Comolli, R., Liga, C., Mazzucchelli, F., Proietto, A., Rota, N., Colombo, G., Bassano, B., Viterbi, R., Padoa-Schioppa, E., 2020. Evaluation of ecosystem services in a protected mountain area: Soil organic carbon stock and biodiversity in alpine forests and grasslands. Ecosyst. Serv. 44, 101135. https://doi.org/10.1016/j.ecoser.2020.101135

Cardelli, V., De Feudis, M., Fornasier, F., Massaccesi, L., Cocco, S., Agnelli, A., Weindorf, D.C., Corti, G., 2019. Changes of topsoil under *Fagus sylvatica* along a small latitudinal-altitudinal gradient. Geoderma 344, 164–178. https://doi.org/10.1016/J.GEODERMA.2019.01.043

Carrari, E., Ampoorter, E., Bottalico, F., Chirici, G., Coppi, A., Travaglini, D., Verheyen, K., Selvi, F., 2017. The old charcoal kiln sites in Central Italian forest landscapes. Quat. Int. 458, 214–223. https://doi.org/10.1016/j.quaint.2016.10.027

Cartocci, A., Fedi, M.E., Taccetti, F., Benvenuti, M., Chiarantini, L., Guideri, S., 2007. Study of a metallurgical site in Tuscany (Italy) by radiocarbon dating. Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms 259, 384–387. https://doi.org/10.1016/j.nimb.2007.01.183

Chantigny, M. H., 2003. Dissolved and water-extractable organic matter in soils: a review on the influence of land use and management practices, Geoderma 113, issues 3–4, 357-380. https://doi.org/10.1016/S0016-7061(02)00370-1.

Chapin, F.S. III; Matson, P.A., Mooney, H.A., 2011. Principles of Terrestrial Ecosystem Ecology. Springer, Heidelberg, Germany.

Cheng, X., Han, H., Zhu, J., Peng, X., Li, B., Liu, H., Epstein, H.E., 2021. Forest thinning and organic matter manipulation drives changes in soil respiration in a *Larix principis-rupprechtii* plantation in China. Soil Tillage Res. 211, 104996. https://doi.org/10.1016/j.still.2021.104996

Chiarantini, L., Benvenuti, M., Costagliola, P., Dini, A., Firmati, M., Guideri, S., Villa, I.M., Corretti, A., 2018. Copper metallurgy in ancient Etruria (southern Tuscany, Italy) at the Bronze-Iron Age transition: a lead isotope provenance study. J. Archaeol. Sci. Reports 19, 11–23. https://doi.org/10.1016/j.jasrep.2018.02.005

Chiti T., Sirca C., Rodeghiero M., Spano D., Valentini R. (2015) Soil Carbon Stocks and Fluxes. In: Valentini R., Miglietta F. (eds) The Greenhouse Gas Balance of Italy. Environmental Science and Engineering. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-32424-6_8

Cocco, S., Agnelli, A., Gobran, G.R., Corti, G., 2013. Changes induced by the roots of *Erica arborea* L. to create a suitable environment in a soil developed from alkaline and fine-textured marine sediments. Plant Soil 368, 297–313. https://doi.org/10.1007/s11104-012-1501-3

Cools, N., Vesterdal, L., De Vos, B., Vanguelova, E., Hansen, K., 2014. Tree species is the major factor explaining C: N ratios in European forest soils. For. Ecol. Manage. 311, 3–16. https://doi.org/10.1016/j.foreco.2013.06.047

Corral-Fernández, R., Parras-Alcántara, L., Lozano-García, B., 2013. Stratification ratio of soil organic C, N and C:N in Mediterranean evergreen oak woodland with conventional and organic tillage. Agric. Ecosyst. Environ. 164, 252–259. https://doi.org/10.1016/J.AGEE.2012.11.002

Corti, G., Agnelli, A., Cocco, S., Cardelli, V., Masse, J., Courchesne, F., 2019. Soil affects throughfall and stemflow under Turkey oak (*Quercus cerris* L.). Geoderma 333, 43–56. https://doi.org/10.1016/J.GEODERMA.2018.07.010

Corti, G., Agnelli, A., Ugolini, F.C., 1997. Release of Al by hydroxy-interlayered vermiculite and hydroxy-interlayered smectite during determination of cation exchange capacity in fine earth and rock fragments fractions. Eur. J. Soil Sci. 48, 249–262. https://doi.org/10.1111/j.1365-2389.1997.tb00545.x

Corti, G., Ugolini, F.C., Agnelli, A., 1998. Classing the soil skeleton (greater than two millimeters): Proposed ppproach and procedure. Soil Sci. Soc. Am. J. 62, 1620–1629. https://doi.org/10.2136/sssaj1998.03615995006200060020x

Corti, G., Ugolini, F.C., Agnelli, A., Certini, G., Cuniglio, R., Berna, F., Fernández Sanjurjo, M.J., 2002. The soil skeleton, a forgotten pool of carbon and nitrogen in soil. Eur. J. Soil Sci. 53, 283–298. https://doi.org/10.1046/j.1365-2389.2002.00442.x

Corvasce, M., Zsolnay, A., D'Orazio, V., Lopez, R., Miano, T.M., 2006. Characterization of water extractable organic matter in a deep soil profile. Chemosphere 62, 1583–1590. https://doi.org/10.1016/J.CHEMOSPHERE.2005.07.065

Cuniglio, R., Corti, G., Agnelli, A., 2009. Rock fragments evolution and nutrients release in vineyard soils developed on a thinly layered limestone (Tuscany, Italy). Geoderma 148, 375–383. https://doi.org/10.1016/J.GEODERMA.2008.11.005

Cutini A., 1996. The influence of drought and thinning on leaf area index estimates from canopy transmittance method. Annales des Sciences Forestieres 53 (2-3): 595 – 603.

Cutini, A., Ferretti, M., Bertini, G., Brunialti, G., Bagella, S., Chianucci, F., Fabbio, G., Fratini, R., Riccioli, F., Caddeo, C., Calderisi, M., Chiucci, B., Corradini, S., Cristofolini, F., Di Salvatore, U., Ferrara, C., Frati, L., Landi, S., Marchino, L., Patteri, G., Piovosi, M., Roggero, P.P., Seddaiu, G., Gottardini, E., 2021. Testing an expanded set of sustainable forest management indicators in Mediterranean coppice area. Ecological Indicators. 130, 108040. https://doi.org/10.1016/j.ecolind.2021.108040

De Feudis, M., Cardelli, V., Massaccesi, L., Hofmann, D., Berns, A.E., Bol, R., Cocco, S., Corti, G., Agnelli, A., 2017. Altitude affects the quality of the water-extractable organic matter (WEOM) from rhizosphere and bulk soil in European beech forests. Geoderma 302, 6–13. https://doi.org/10.1016/j.geoderma.2017.04.015

De Feudis, M., Cardelli, V., Massaccesi, L., Trumbore, S.E., Vittori Antisari, L., Cocco, S., Corti, G., Agnelli, A., 2019. Small altitudinal change and rhizosphere affect the SOM light fractions but not the heavy fraction in European beech forest soil. Catena 181, 104091. https://doi.org/10.1016/j.catena.2019.104091

De Nicola, C., Zanella, A., Testi, A., Fanelli, G., Pignatti, S., 2014. Humus forms in a Mediterranean area (Castelporziano Reserve, Rome, Italy): classification, functioning and organic carbon storage. Geoderma 235–236, 90-99. https://doi.org/10.1016/j.geoderma.2014.06.033.

Diao, M., Yang, K., Zhu, J., Li, M., Xu, S., 2020. Native broad-leaved tree species play key roles on maintaining soil chemical and microbial properties in a temperate secondary forest, Northeast China. Forest Ecology and Management. 462, 117971. https://doi.org/10.1016/j.foreco.2020.117971

Fabbio, G., 2016. Coppice forests, or the changeable aspect of things, a review. Annuals of Silvicultural Research. 40, 108-132. http://dx.doi.org/10.12899/asr-1286

Fabbio, G., Amorini, E., 2006. Avviamento ad altofusto e dinamica naturale nei cedui a prevalenza di cerro. Risultati di una prova sperimentale a 35 anni dalla sua impostazione. Il protocollo di Caselli (Pisa). Ann. Ist. Sper. di Selvic. 33, 79–104. https://journals-crea.4science.it/index.php/asr/issue/viewIssue/154/8

Fabbio, G, Cutini, A, 2017. Il ceduo oggi: quale gestione oltre le definizioni? Forest@ - Journal of Silviculture and Forest Ecology, Volume 14, Pages 257-274. https://doi.org/10.3832/efor2562-014

Frati, L., Brunialti, G., Landi, S., Filigheddu, R., Bagella, S., 2021. Exploring the biodiversity of key groups in coppice forests (Central Italy): the relationship among vascular plants, epiphytic lichens, and wood-decaying fungi. Plant Biosystems, 1-12.

Garlato, A., Obber, S., Vinci, I., Mancabelli, A., Parisi, A., Sartori, G., 2009a. La determinazione dello stock di carbonio nei suoli del Trentino a partire dalla banca dati della carta dei suoli alla scala 1:250.000. Museo Tridentino di Scienze Naturali. Trento Studi Trent Sci Nat 85, 157–160.

Garlato, A., Obber, S., Vinci, I., Sartori, G., Manni, G., 2009b. Stock attuale di carbonio organico nei suoli di montagna del Veneto. Museo Tridentino di Scienze Naturali. Trento Studi Trent Sci Nat 85, 69–8.

Gartzia-Bengoetxea, N., Virto, I., Arias-González, A., Enrique, A., Fernández-Ugalde, O., Barré, P., 2020. Mineral control of organic carbon storage in acid temperate forest soils in the Basque Country. Geoderma 358, 113998. https://doi.org/10.1016/j.geoderma.2019.113998

Gong, C., Tan, Q., Liu, G., Xu, M., 2021. Forest thinning increases soil carbon stocks in China. Forest Ecology and Management 482, 118812. https://doi.org/10.1016/j.foreco.2020.118812

Gressel, N., McColl, J.G., Preston, C.M., Newman, R.H., Powers, R.F., 1996. Linkages between phosphorus transformations and carbon decomposition in a forest soil. Biogeochemistry 33, 97–123. https://doi.org/10.1007/BF02181034

Gross, C.D., James, J.N., Turnblom, E.C., Harrison, R.B., 2018. Thinning treatments reduce deep soil carbon and nitrogen stocks in a Coastal Pacific Northwest forest. Forests 9, 238. https://doi.org/10.3390/f9050238

Guermandi, M., Marchi, N., Tarocco, P., Calzolari, C., Ungaro, F., Villani, I., 2013. Siti locali rappresentativi dei suoli della pianura e della collina Emiliano-Romagnola. In: Emilia-Romagna, Regione (Ed.), Servizio Geologico, Sismico e dei Suoli. IRPI CNR, Provincia di Ferrara (41 pp.).

Gutiérrez-Girón, A., Díaz-Pinés, E., Rubio, A., Gavilán, R.G., 2015. Both altitude and vegetation affect temperature sensitivity of soil organic matter decomposition in Mediterranean high mountain soils. Geoderma 237–238, 1–8. https://doi.org/10.1016/j.geoderma.2014.08.005

Haynes, R.J. 1990. Active ion uptake and maintenance of cation-anion balance: A critical examination of their role in regulating rhizosphere pH. Plant Soil, 126: 247–264.

He, Z., Fang, S., Chen, L., Du, J., Zhu, X., Lin, P., 2018. Spatial patterns in natural *Picea crassifolia* forests of northwestern China, as basis for close-to-nature forestry. Journal of Mountain Science 15, 1909-1919. https://doi.org/10.1007/s11629-016-3998-z

Hölscher, D., Schade, E., Leuschner, C., 2001. Effects of coppicing in temperate deciduous forests on ecosystem nutrient pools and soil fertility. Basic Appl. Ecol. 2, 155–164. https://doi.org/10.1078/1439-1791-00046

Jenny, H., 1941. Factors of Soil Formation. McGraw-Hill.

Kaiser, M., Zederer, D.P., Ellerbrock, R.H., Sommer, M., Ludwig, B., 2016. Effects of mineral characteristics on content, composition, and stability of organic matter fractions separated from seven forest topsoils of different pedogenesis. Geoderma 263, 1–7. https://doi.org/10.1016/j.geoderma.2015.08.029

Kleber M., 2010. What is recalcitrant soil organic matter?. Environmental Chemistry 7, 320-332.

https://doi.org/10.1071/EN10006

Kögel-Knabner, I., Ekschmitt, K., Flessa, H., Guggenberger, G., Matzner, E., Marschner, B. and von Lützow, M., 2008. An integrative approach of organic matter stabilization in temperate soils: Linking chemistry, physics, and biology. Z. Pflanzenernähr. Bodenk., 171, 5-13. https://doi.org/10.1002/jpln.200700215

Lee, J.H., Lee, J.G., Jeong, S.T., Gwon, H.S., Kim, P.J., Kim, G.W., 2020. Straw recycling in rice paddy: Trade-off between greenhouse gas emission and soil carbon stock increase. Soil Tillage Res. 199, 104598. https://doi.org/10.1016/J.STILL.2020.104598

Lehmann, J., Kleber, M., 2015. The contentious nature of soil organic matter. Nature 528, 60-68. https://doi.org/10.1038/nature16069

Lemanceau, P., Bauer, P., Kraemer, S., Briat, J.-F., 2009. Iron dynamics in the rhizosphere as a case study for analyzing interactions between soils, plants and microbes. Plant Soil 321, 513–535. https://doi.org/10.1007/s11104-009-0039-5

Mairota, P., Neri, F., Travaglini, D., Picchio, R., Terzuolo, P. G., Piussi P., Marchi, M., 2018. Chapter 6 "Thirty-Five Countries". In A. Unrau, G. Becker, R. Spinelli, D. Lazdina, N. Magagnotti, V.N. Nicolescu, P. Buckley, D. Bartlett, P.D. Kofman (Eds.), Coppice Forests in Europe (pp. 269-282). Freiburg i. Br., Germany: Albert Ludwig University of Freiburg.

Manetti, M.C., Becagli, C., Bertini, G., Cantiani, P., Marchi, M., Pelleri, F., Sansone, D., Fabbio, G., 2020. The conversion into high forest of Turkey oak coppice stands: methods, silviculture and perspectives. iForest 13: 309-317. - doi: 10.3832/ifor3483-013

Manetti, M.C., Gugliotta, O.I., 2006. Effetto del trattamento di avviamento ad altofusto sulla diversità specifica e strutturale delle specie legnose in un ceduo di cerro. Ann. Ist. Sper. di Selvic. 33, 105-114. https://journals-crea.4science.it/index.php/asr/issue/viewIssue/154/8

Marchi, E., Picchio, R., Mederski, P.S., Vusić, D., Perugini, M., Venanzi, R., 2016. Impact of silvicultural treatment and forest operation on soil and regeneration in Mediterranean Turkey oak (*Quercus cerris* L.) coppice with standards. Ecol. Eng. 95, 475–484.

https://doi.org/10.1016/j.ecoleng.2016.06.084

Marinari, S., Marabottinia, R., Falsone, G., Vianello, G., Vittori Antisari, L., Agnelli, A., Massaccesi, L., Cocco, S., Cardelli, V., Serrani, D., Corti, G., 2021. Mineral weathering and lessivage affect microbial community and enzyme activity in mountain soils. Appl. Soil Ecol. 167, 104024. https://doi.org/10.1016/j.apsoil.2021.104024

Mason, J.A., Zanner, C.W., 2005. Grassland Soils. Encycl. Soils Environ. 4, 138–145. https://doi.org/10.1016/B0-12-348530-4/00028-X

Mayer, M., Prescott, C.E., Abaker, W.E.A., Augusto, L., Cécillon, L., Ferreira, G.W.D., James, J., Jandl, R., Katzensteiner, K., Laclau, J.P., Laganière, J., Nouvellon, Y., Paré, D., Stanturf, J.A., Vanguelova, E.I., Vesterdal, L., 2020. Tamm review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. For. Ecol. Manage. 466, 118127. https://doi.org/https://doi.org/10.1016/j.foreco.2020.118127

Nelson, D.W., Sommers, L.E., 1996. Total Carbon, Organic Carbon, and Organic Matter, in Sparks, D., Page, A., Helmke, P., Loeppert, R.H., Soltanpour, P.N. Tabatabai, M.A., Johnston, C.T., Sumner, M.E. (Eds.), Methods of Soil Analysis. SSSA Book Series. https://doi.org/10.2136/sssabookser5.3.c34

Ni, X., Lin, C., Chen, G., Xie, J., Yang, Z., Liu, X., Xiong, D., Xu, C., Yue, K., Wu, F., Yang, Y., 2021. Decline in nutrient inputs from litterfall following forest plantation in subtropical China. Forest Ecol. and Manag., 496, 119445. https://doi.org/10.1016/j.foreco.2021.119445.

Olsen, S.R., Cole, C.V., Watanabe, F.S. and Dean, L.A. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate, USDA. Circular 939

Ono, K., Hiradate, S., Morita S., Hirai, K., 2013. Fate of organic carbon during decomposition of different litter types in Japan. Biogeochem. 112, 7-12. https://doi.org/10.1007/s10533-011-9682-z

Pistocchi, C., Mészáros, É., Tamburini, F., Frossard, E., Bünemann, E.K., 2018. Biological processes dominate phosphorus dynamics under low phosphorus availability in organic horizons of temperate forest soils. Soil Biol. Biochem. 126, 64–75. https://doi.org/10.1016/j.soilbio.2018.08.013

Prasad Dangal, S., Kumar Das, A., Shyam Krishna, P., 2017. Effectiveness of management interventions on forest carbon stock in planted forests in Nepal. J. Environ. Manage. https://doi.org/10.1016/j.jenvman.2017.03.056

Prescott, C.E., 2002. The influence of the forest canopy on nutrient cycling. Tree Physiol. 22, 1193–1200. https://doi.org/10.1093/treephys/22.15-16.1193

Quénard, L., Samouëlian, A., Laroche, B., Cornu, S., 2011. Lessivage as a major process of soil formation: A revisitation of existing data. Geoderma 167–168, 135–147. https://doi.org/10.1016/J.GEODERMA.2011.07.031

Richter, D. de B., Oh, N.H., Fimmen, R., Jackson, J., 2007. The Rhizosphere and Soil Formation. Rhizosph. 179-IN2. https://doi.org/10.1016/B978-012088775-0/50010-0

Scharenbroch, B.C., Bockheim, J.G., 2007. Impacts of forest gaps on soil properties and processes in old growth northern hardwood-hemlock forests. Plant and Soil. 294, 219-233. https://doi.org/10.1007/s11104-007-9248-y

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Soil Survay Staff., 2012. Field Book for Describing and Sampling Soils, Version 3.0. https://doi.org/10.1038/258254a0

Schrumpf, M., Kaiser, K., Guggenberger, G., Persson, T., Kögel-Knabner, I., Schulze, E.D., 2013. Storage and stability of organic carbon in soils as related to depth, occlusion within aggregates, and attachment to minerals. Biogeosciences 10, 1675–1691. https://doi.org/10.5194/bg-10-1675-

Society of American Foresters (SAF), 2008. Dictionary of Forestry. Retrieved 1 February 2015. http://dictionaryofforestry.org/dict/term/forest_management

Soil Survey Staff, 2014. Keys to Soil Taxonomy, 12th edition. USDA–Natural Resources Conservation Service, Washington.

Song, G., Li, L., Pan, G., Zhang, Q., 2005. Topsoil organic carbon storage of China and its loss by cultivation. Biogeochemistry 74, 47–62. https://doi.org/10.1007/s10533-004-2222-3

Sundquist, E.T., Visser, K., 2003. 8.09 - The Geologic History of the Carbon Cycle. Treatise on Geochemistry. Pergamon (Ed.), 8-9, 425-472. US Geological Survey, Woods Hole, MA, United States. https://doi.org/10.1021/j100244a025

Tiessen, H., Cuevas, E., Chacon, P., 1994. The role of soil organic matter in sustaining soil fertility. Nature 371, 783–785. https://doi.org/10.1038/371783a0

Trumbore, S. 2000. Age of soil organic matter and soil respiration: radiocarbon constraints on belowground C dynamics. Belowground Processes and Global Change 10, 399-411.

Ugolini, F.C., Corti, G., Agnelli, A., Piccardi, F., 1996. Mineralogical, physical, and chemical properties of rock fragments in soil. Soil Sci. 161, 521-542. https://doi.org/10.1097/00010694-199608000-00007

Unrau, A., Becker, G., Spinelli, R., Lazdina, D., Magagnotti, N., Nicolescu, V.-N., Buckley P., Bartlett D, Kofman, P. D.. (Eds.). 2018. Coppice Forests in Europe. EuroCoppice COST Action. Albert Ludwig University of Freiburg, Germany. Retrieved from https://www.eurocoppice.unifreiburg.de/coppice-forests-in-europe.

Vesterdal, L., Dalsgaard, M., Felby, C., Raulund-Rasmussen, K., Jørgensen, B.B., 1995. Effects of thinning and soil properties on accumulation of carbon, nitrogen and phosphorus in the forest floor of Norway spruce stands. For. Ecol. Manage. 77, 1–10. https://doi.org/10.1016/0378-1127(95)03579-Y

Wang, L., Amelung, W., Prietzel, J., Willbold, S., 2019. Transformation of organic phosphorus compounds during 1500 years of organic soil formation in Bavarian Alpine forests – A 31P NMR study. Geoderma, 340, 192-205. https://doi.org/10.1016/j.geoderma.2019.01.029

Wang, M.C., Chang, S.H., 2001. Mean residence times and characteristics of humic substances extracted from a Taiwan soil. Can. J. Soil Sci. 81, 299-307.

Wattel-Koekkoek, E.J.W., Buurman, P., van der Plicht, J., Wattel, E., van Breemen, N., 2003. Mean residence time of soil organic matter associated with kaolinite and smectite. Eur. J. Soil Sci. 54, 1-10.

Webster, R., 2001. Statistics to support soil research and their presentation. European Journal of Soil Science. 52, 331-340. https://doi.org/10.1046/j.1365-2389.2001.00383.x

Wu, J., Zeng, H., Zhao, F., Chen, C., Liu, W., Yang, B., Zhang, W., 2020. Recognizing the role of plant species composition in the modification of soil nutrients and water in rubber agroforestry systems. Sci. Total Environ. 723, 138042. https://doi.org/10.1016/j.scitotenv.2020.138042

Yao, S., Zhang, Y.L., Han, Y., Han, X.Z., Mao, J.D., Zhang, B., 2019. Labile and recalcitrant components of organic matter of a Mollisol changed with land use and plant litter management: An advanced 13C NMR study. Sci. of The Total Environ., 660, 1-10. https://doi.org/10.1016/j.scitotenv.2018.12.403

Zhang, H., Deng, Q., Hui, D., Wu, J., Xiong, X., Zhao, J., Zhao, M., Chu, G., Zhou, G., Zhang, D., 2019. Recovery in soil carbon stock but reduction in carbon stabilization after 56-year forest restoration in degraded tropical lands. For. Ecol. Manage. 441, 1–8. https://doi.org/10.1016/J.FORECO.2019.03.037

Zhang, X., Guan, D., Li, W., Sun, D., Jin, C., Yuan, F., Wang, A., Wu, J., 2018. The effects of forest thinning on soil carbon stocks and dynamics: A meta-analysis. For. Ecol. Manage. 429, 36–43. https://doi.org/10.1016/j.foreco.2018.06.027

Zhao, Q., Bai, J., Wang, X., Zhang, W., Huang, Y., Wang, L., Gao, Y., 2019. Soil organic carbon content and stock in wetlands with different hydrologic conditions in the Yellow River Delta, China. Ecohydrol. Hydrobiol. 20, 537-547. https://doi.org/10.1016/J.ECOHYD.2019.10.008

Appendix – Supplementary data

Table S1. General features of each study plot (≈900 m^2) and morphology of the profiles under *Quercus cerris* L. Natural Reserve of Monterufoli-Caselli forest, Tuscany, Italy. For symbols see legend.

<table>
<tr><th>Horizon[a]</th><th>Depth</th><th>Thickness</th><th>Colour[b]</th><th>Structure[c]</th><th>Consistence[d]</th><th>Roots[e]</th><th>Boundary[f]</th><th>Skeleton</th><th>Other observations[g]</th></tr>
<tr><th></th><th colspan="2">cm</th><th></th><th></th><th></th><th></th><th></th><th>%</th><th></th></tr>
<tr><td colspan="10">Heavy thinning: 578 stems per ha released for coppice conversion into high forest</td></tr>
<tr><td colspan="10">Plot 3. (43.20962N, 10.70267E) Slope 15-18%; Exposure: NNE. Altitude: 337-342 m – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm.
Presence of a charcoal kiln. The surface shows a large presence of rock outcrop. Light wild boar activity. Emerging rock: 80%; Boulders: 5%. Soil cover: 95%. Understorey cover: 80%. Moss cover: 70% (including rock outcrop). Vegetation. Trees: Quercus cerris L. (90%), Fraxinus ornus L., Ostrya carpinifolia Scop.. Bushes: Ruscus aculeatus L. (20%), Cornus sanguinea L., Crataegus monogyna Jacq., Hedera helix L., Pteridium aquilinum L. Kuhn. Herbaceous layer: Cyclamen spp. Parent material: limestone.
Soil (Soil Survey Staff, 2014): fine, mixed, mesic Lithic Humustept.</td></tr>
<tr><td>OLn</td><td>6-3</td><td>2-3</td><td>-</td><td>-</td><td>-</td><td>0</td><td>cw</td><td>5</td><td>Light wild boar turbation. Undecomposed leaves and branch fragments of Q. cerris, F. ornus, R. aculeatus</td></tr>
<tr><td>OLv</td><td>3-2</td><td>2-3</td><td>-</td><td>-</td><td>-</td><td>0</td><td>cw</td><td>5</td><td>Light wild boar turbation. Undecomposed leaves and branch fragments of Q. cerris, F. ornus, R. aculeatus</td></tr>
<tr><td>OH</td><td>2-0</td><td>1-3</td><td>10YR 3/2</td><td>-</td><td>-</td><td>1mi,vf</td><td>cw</td><td>5</td><td>A few mycelium</td></tr>
<tr><td>A</td><td>0-2</td><td>1-3</td><td>10YR 3/1</td><td>2-3m abk+cr</td><td>fr</td><td>3mi,vf,f,m</td><td>cw</td><td><1</td><td>A few mycelium between A and Bw1</td></tr>
<tr><td>Bw1</td><td>2-12</td><td>8-12</td><td>10YR 4/2</td><td>2f,m sbk</td><td>fr</td><td>2mi,vf,f; 1m</td><td>cw</td><td><1</td><td>A few thin cutans</td></tr>
<tr><td>Bw2</td><td>12-30</td><td>14-19</td><td>10YR 4/3</td><td>2-3m abk</td><td>fr</td><td>2mi,vf,f; 3m</td><td>cw</td><td><1</td><td>Common moderate cutans</td></tr>
<tr><td>C&Bw3</td><td>30-36</td><td>5-9</td><td>10YR 4/4</td><td>2m abk</td><td>fr</td><td>1mi,vf,f,m; 1c</td><td>ci</td><td>30</td><td>Common thin cutans</td></tr>
<tr><td>C</td><td>36-45+</td><td>-</td><td>10YR 5/4</td><td>-</td><td>-</td><td>$v_1$vf,f,m,c</td><td>-</td><td>60</td><td>A few cutans</td></tr>
<tr><td colspan="10">Plot 5. (43.21013N, 10.70353E) Slope 7-12%; Exposure: NNW; Altitude: 338-341 m – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm.
Emerging rock: 15%. Soil cover: 90%. Understorey cover: 60%. Moss cover: 5%. Vegetation. Trees: Quercus cerris L. (80%), Fraxinus ornus L., Ulmus spp., Ostrya carpinifolia L., Quercus ilex L. Bushes: Ruscus aculeatus L. (60%), Cornus sanguinea L., Crataegus monogyna Jacq., Smilax aspera L., Rubus ulmifolius Schott., Daphne laureola L., Hedera helix L., Pteridium aquilinum (L.) Kunh Herbaceous layer: Cyclamen spp.. Parent material: limestone.
Soil (Soil Survey Staff, 2014): fine, mixed, mesic Typic Humustept.</td></tr>
<tr><td>OLn</td><td>7-3</td><td>2-5</td><td>-</td><td>-</td><td>-</td><td>0</td><td>cw</td><td>15</td><td>Undecomposed leaves and branch fragments of Q. cerris, F. ornus, R. aculeatus, Q. ilex</td></tr>
<tr><td>OLv</td><td>3-1</td><td>2-3</td><td>-</td><td>-</td><td>-</td><td>0</td><td>cw</td><td>15</td><td>Undecomposed leaves and branch fragments of Q. cerris, F. ornus, R. aculeatus, Q. ilex</td></tr>
<tr><td>OH</td><td>1-0</td><td>0.5-1</td><td>7.5YR 3/2</td><td>-</td><td>-</td><td>1mi,vf,f</td><td>cw</td><td>15</td><td>A few mycelium and mesofauna</td></tr>
<tr><td colspan="10">Left part of soil profile</td></tr>
<tr><td>A</td><td>0-2</td><td>1-2</td><td>7.5YR 3/2</td><td>2f,m sbk</td><td>fr</td><td>2mi,vf,f,m</td><td>cw</td><td>20</td><td>A few mesofauna</td></tr>
<tr><td>Bw1</td><td>2-.18</td><td>14-16</td><td>7.5YR 4/3</td><td>3f,m sbk</td><td>fr</td><td>2m,vf,f; 3mco</td><td>cw</td><td>20</td><td>A few thin cutans</td></tr>
<tr><td>Bw2</td><td>18-57+</td><td>35-40</td><td>10YR 4/4</td><td>2f,m abk</td><td>fr</td><td>2m,vf,f,m; 3co</td><td>cw</td><td>20</td><td>Common thin cutans</td></tr>
<tr><td colspan="10">Central part of soil profile</td></tr>
<tr><td>A</td><td>0-4</td><td>1-3</td><td>7.5YR 3/2</td><td>2f,m sbk</td><td>fr</td><td>2mi,vf,f,m</td><td>cw</td><td>20</td><td>A few mesofauna</td></tr>
<tr><td>AB</td><td>4-19</td><td>8-15</td><td>7.5YR 4/3</td><td>3f,m sbk</td><td>fr</td><td>2mi,vf,f; 3m</td><td>cw</td><td>20</td><td></td></tr>
</table>

Bw	19-59+	20-40	10YR 4/4	2f,m abk	fr	2mi,vf,f,m; 3co	cw	20	A few thin cutans
						Right part of soil profile			
A	0-2	1-2	7.5YR 3/2	2f,m sbk	fr	2mi,vf,f,m	cw	20	A few mesofauna
Bw1	2-22	15-20	10YR 4/4	2f,m sbk	fr	2mi,vf,f,m,co	cw	25	A few thin cutans
Bw2	22-60+	28-38	10YR 4/4	2f,m abk	fr	2mi,vf,f,m; 3co	cw	25	Common thin cutans

Plot 7. (43.2074N, 10.70071E) Slope 15-20%; Exposure: NNE; Altitude: 340-345 m – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm.
Emerging rock: 5%. Soil cover: 95%. Understorey cover: 50%. Moss cover: 5%. Vegetation. Trees: *Quercus cerris* L. (90%), *Fraxinus ornus* L., *Ostrya carpinifolia* Scop., *Quercus ilex* L. Bushes: *Ruscus aculeatus* L. (50%), *Cornus sanguinea* L., *Crataegus monogyna* Jacq., *Smilax aspera* L., *Rubus ulmifolius* Schott., *Daphne laureola* L., *Hedera helix* L.. Herbaceous layer: *Cyclamen* spp.. Parent material: limestone.
Soil (Soil Survey Staff, 2014): fine, mixed, mesic Typic Humustept.

OLn	10-6	3-6	-	-	-	0	cw	5	Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, R. aculeatus*, *Q. ilex*
OLv	6-5	1-2	-	-	-	0	cw	5	Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, R. aculeatus*, *Q. ilex*. A few mycelium
OH1	5-2	3-4	7.5YR 3/3	-	-	1mi,vf; 3f	cs	5	A few mycelium. Mesofauna
OH2	2-0	1-2	7.5YR 3/2	-	-	2mi,vf; 3f	cs		A few mycelium. Mesofauna
A	0-2	2-12	7.5YR 3/2	2f,m cr+sbk	fr	1mi,vf,f; 3m	ci	10	Minute skeleton
Bw	2-17	15-26	7.5YR 5/6	2f,m abk-sbk	fr	1mi,vf,f	cb	2	A few thin cutans
Bg1	17-41	20-26	10YR 5/6 10YR 4/2	2f,m sbk-abk	fr	1mi,vf,f	cw	<1	Abundant cutans
Bg2	41-69	25-28	10YR 5/8 10YR 5/2	2m sbk-abk	fr	1mi,vf; 3f; 1m,co	cw	<1	Abundant thick cutans
Bg3	69-84	13-14	10YR 5/4	2f,m sbk-abk	fr	v1mi,vf,f,m,co	cw	<1	Abundant moderate cutans
BC	84-95+	-	10YR 6/3	2m abk	fr	v1mi,vf,f,m,co	-	5	Common moderate cutans

Plot 11. (43.20801N, 10.70108) Steep slope 15-20%; Exposure: NNW; Altitude: 340-344 m – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm.
Emerging rock: 10%. Soil cover: 95%. Understorey cover: 60%. Moss cover: 5%. Vegetation. Trees: *Quercus cerris* L. (90%), *Fraxinus ornus* L., *Ostrya carpinifolia* Scop., *Quercus ilex* L.. Bushes: *Ruscus aculeatus* L. (60%), *Cornus sanguinea* L., *Crataegus monogyna* Jacq., *Smilax aspera* L., *Rubus ulmifolius* Schott, *Daphne laureola* L., *Hedera helix* L., *Pteridium aquilinum* (L.) Kunh. Herbaceous layer: *Cyclamen* spp.. Parent material: limestone.
Soil (Soil Survey Staff, 2014): fine, mixed, mesic Typic Humustept.

OLn	8-4	3-10	-	-	-	0	cw	10	Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, R. aculeatus*, *C. sanguinea*, *Q. ilex*
OLv	4-2	2-5	-	-	-	0	cw	10	Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, R. aculeatus*, *C. sanguinea*, *Q. ilex*
OFr	2-1	2-3	-	-	-	v1mi	cw	10	
OH	1-0	0.5-1	7.5YR 2.5/1	-	-	1mi,vf	cs	10	A few mycelium
A	0-3	1-2	7.5YR 2.5/1	3f sbk+cr	fr	1mi,vf; 2f	cw	2-3	
Bw1	3-18	10-15	10YR 6/6	2f,m abk	fr	1mi,vf; 2f,m,co	cw	25	A few thin cutans
Bw2	18-69	40-50	10YR 5/8	1m abk	fr	1mi,vf; 2f; 3m,co	cw	50	Common moderate cutans

BC	69-83	10-13	10YR 5/6	1m sbk	fr	1mi,vf,f,m	cw	60	A few thin cutans
Cr	83-86+	-	-	-	-	v1mi,vf,f	-	75	

Moderate thinning: 869 stems per ha released for coppice conversion into high forest

Plot 1. (43.20983N, 10.70421E). Slope 10-12%; Exposure: NNE. Altitude: 337-340 m – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm.
The ground surface shows the presence of two small gorges (about 20% of the soil surface cover) and intense wild boar activity; the presence of *Ruscus aculeatus* L. restricts the wild boar activity on uncovered areas, where soil shows a lamellar structure due to trampling. Emerging rock: 30%. Soil cover: 90%. Understorey cover: 50%. Moss cover: 5-10%. Vegetation. Trees: *Quercus cerris* L.(80%), *Fraxinus* spp., *Ulmus* spp., *Ostrya carpinifolia* Scop., *Quercus ilex* L. Bushes: *Ruscus aculeatus* L.(50%), *Crataegus monogyna* Jacq., *Daphne laureola* L.,. Herbaceous layer: *Cyclamen* spp. Parent material: limestone.
Soil (Soil Survey Staff, 2014): fine, mixed, mesic Typic Humustept.

OLn	6-4	1-3	-	-	-	0	cw	30	Intense wild boar turbation. Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, Q, ilex, R. aculeatus*
OLv	4-2	1-3	-	-	-	2mi,vf,f	cw	30	Intense wild boar turbation. Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, Q. ilex, R. aculeatus*
OH	2-0	1-3	7.5YR 3/2	-	-	2-3mi,vf,f; 1m	cw	30	Intense wild boar turbation. Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, R. aculeatus*. Spiders and ants
A	0-2	2-5	7.5YR 3/1	2tn,m pl→m abk	fr	2mi,vf,f,m,co	aw	30	Intense wild boar turbation. A few mycelium
Bw1	2-25	20-25	10YR 4/6	2m abk	fr	2mi,vf,f; 1m,co	cw	20	A few mycelium. A few thin cutans
Bw2	25-34	7-10	10YR 4/3	2m sbk+abk	fr	1mi,vf,f;3m,co	cw	20	A few mycelium. Common moderate cutans
Bw3	34-80	32-44	10YR 4/3	2-3m sbk+abk	fr	1mi,vf,f; 2m,co	cw	30	Common moderate cutans
Cr	80-83+	-	10YR 5/2	1m abk	fr	1mi,vf,f,m,co	-	80	Common thin cutans (7.5YR 3/1 color)

Plot 4. (43.20848N, 10.70334E) Slope 15-20%; Exposure: N. Altitude: 337-343 m – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm.
Intense wild boar activity. Emerging rock: 20%. Soil cover: 90%. Understorey cover: 50%. Moss cover: 5%. Vegetation. Trees: *Quercus cerris* L.(90%), *Fraxinus* spp., *Ulmus* spp., *Ostrya carpinifolia* Scop., *Quercus ilex* L. Bushes: *Ruscus aculeatus* L. (50%), *Crataegus monogyna* Jacq.(20%). Herbaceous layer: *Cyclamen* spp.. Parent material: limestone.
Soil (Soil Survey Staff, 2014): fine, mixed, mesic Typic Humustept.

OLn	6-3	2-5	-	-	-	0	cw	20	Intense wild boar turbation. Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, Q. ilex, R. aculeatus*
OLv	3-1	2-3	-	-	-	0	cw	20	Intense wild boar turbation. Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, Q. ilex, R. aculeatus*
OH	1-0	0.5-1	7.5YR 3/2	-	-	1mi,vf	cw	20	Intense wild boar turbation. A few mycelium, mesofauna and earthworms
A	0-2	0.5-2	7.5YR 3/1	3m sbk	fr	2mi,vf,f,m	cw	5	Intense wild boar turbation. Charcoal fragments
AB	2-17	8-15	7.5YR 4/2	2-3m cr+abk+sbk	fr	2mi,vf; 3f,m	cw	5	Charcoal fragments

Bw1	17-43	24-32	7.5YR 4/4	2f,m abk	fr	2mi,vf; 3f,m,co	cw	5	Charcoal fragments. A few mycelium. A few thin cutans
Bw2	43-62	18-20	10YR 5/4	2-3f,m abk	fr	1mi,vf; 2f; 3m,co	cw	5	A few to common thin cutans
Bw3	62-94	28-34	10YR 4/4	2f,m abk	fr	1mi,vf; 2f, co	cw	5	Common to abundant moderate cutans
Bg	94-130	32-38	7.5YR 3/1	2f,m,c abk+sbk	fr	1vf	cw	5	Abundant thick cutans
2A	130-142+	-	10YR 4/1	2f,m abk	fr	1vf	-	2	

Plot 8. (43.20739N, 10.70105E) Slope 15-20%; Exposure: NNE; Altitude: 337-342 m – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm.
Intense wild boar activity. Emerging rock: 10%. Soil cover: 90%. Understorey cover: 60%. Moss cover: 5%. Vegetation. Trees: *Quercus cerris* L.(90%), *Fraxinus* spp., *Ulmus* spp., *Ostrya carpinifolia* Scop., *Quercus ilex* L. Bushes: *Ruscus aculeatus* L.(40%), *Crataegus monogyna* Jacq.(30). Herbaceous layer: *Cyclamen* spp.. Parent material: limestone.
Soil (Soil Survey Staff, 2014): fine, mixed, mesic Typic Humustept.

OLn	10-6	2-7	-	-	-	0	cw	10	Intense wild boar turbation. Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, Q. ilex, R. aculeatus*
OLv	6-4	2-3	-	-	-	0	cw	10	Intense wild boar turbation. Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, Q. ilex, R. aculeatus*
OFr	4-3	2-3	-	-	-	1mi,vf	cw	10	Intense wild boar turbation
OH	3-0	2-3	7.5YR 3/2	-		2mi,vf,f	cs	10	Intense wild boar turbation
A	0-2	1-2	7.5YR 3/2	2f,m cr	fr	1mi,vf; 2f	cw	<1	Intense wild boar turbation. Charcoal fragments
Bw	2-20	14-20	10YR 5/6	2f,m abk-sbk	fr	2mi,vf; 3f,m	cw	<1	Charcoal fragments. A few to common thin cutans
Bg1	20-39	18-22	10YR 5/4	2f,m sbk-abk	fr	2mi,vf; 3f,m,co	cw	<1	Charcoal fragments. Mn nodules. Abundant thick cutans
Bg2	39-67	26-28	10YR 5/8	2f,m abk sbk	fr	1mi,vf; 2f,m,co	cw	<1	A few earthworms. Mn nodules. Common thick cutans
2Bg	67-87	16-23	10YR 7/3	2f,m abk-sbk	fr	1mi,vf,f,m,co	cs	<1	Siltite fragments. A few to common thin cutans
R	87-90+	-	-	-	-	-	-	-	Siltite fragments

Plot 12. (43.20782N, 10.70061E) Slope 5-20%; Exposure: NNW; Altitude: 341-345 m – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm.
The area shows the presence of macro-furrow (about 10%). About 5% of the area has a steep slope of 5% while the remaining part has a bump morphology with a steep slope of 20%. Moderate wild boar activity. Emerging rock: 5%. Soil cover: 95%. Understorey cover: 70%. Moss cover: 5%. Vegetation. Trees: *Quercus cerris* L.(80%), *Fraxinus ornus* L., *Ostrya carpinifolia* Scop., *Quercus ilex* L. Bushes: *Ruscus aculeatus* L.(70%), *Cornus sanguinea* L., *Crataegus monogyna* Jacq., *Smilax aspera* L., *Rubus ulmifolius* Schott., *Daphne laureola* L., *Hedera helix* L., *Pteridium aquilinum* (L.) Kunh Herbaceous layer: *Cyclamen* spp. Parent material: limestone.
Soil (Soil Survey Staff, 2014): fine, mixed, mesic Typic Humustept.

OLn	9-4	5-10	-	-	-	0	cw	5	Moderate wild boar turbation. Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, R. aculeatus*, *Q. ilex, C. sanguinea*

OLv	4-2	2-3	-	-	-	0	cw	5	Moderate wild boar turbation. Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, R. aculeatus*, *Q. ilex, C. sanguinea*
OFr	2-1	1-2	10YR 2/1	-	-	1 mi,vf	cs	5	Moderate wild boar turbation
OH	1-0	0.5-1	10YR 2/1	-	-	1mi,vf	cs	5	Moderate wild boar turbation
A	0-4	2-4	7.5YR 2.5/1	3f,m,c cr	fr	1mi,vf; 3f	cw	0	Moderate wild boar turbation. Charcoal fragments
AB	4-9	4-6	10YR 3/2 10YR 4/3	3m,c cr+abk	fr	1mi,vf; 2f	cw	0	
Bw1	9-32	20-25	10YR 5/6	1m abk	fr	1mi,vf; 2f; 1m	cw	0	A few mycelium. A few thin cutans
Bw2	32-54	20-25	10YR 5/3	1m sbk	fr	1mi,vf; 3m,co	cw	0	Common moderate cutans
Bg	54-97+	38-45	5YR 4/6 10YR 5/6	1m abk	fr	1mi,vf,f,m,co	cs	0	Mn nodules. Abundant thick cutans

Control: 3417 stems per ha; last final rotation cut of coppice implemented in 1949

Plot 2. (43.20947N, 10.7035E) Slope 12-20%; Exposure: NNE; Altitude: 337-341 m – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm.
The surface of this parcel shows a large presence of rock outcrop (≈70%) and a gorge (about 20% of the soil surface cover). The rock outcrop forms an alternation of rock and small gently sloping terraces; on the outcropping rock the soil is absent. Light wild boar activity. Emerging rock: 50%; Boulders: 5%. Soil cover: 90%. Understorey cover: 50%. Moss cover: 10%. Vegetation. Trees: *Quercus cerris* L. (80%), *Fraxinus ornus* L., *Ostrya carpinifolia* Scop.. Bushes: *Ruscus aculeatus* L.(40%), *Cornus sanguinea* L., *Crataegus monogyna* Jacq, *Smilax aspera* L., *Rubus ulmifolius* Schott., *Daphne laureola* L., *Hedera helix* L., *Pteridium aquilinum* (L.) Kunh Herbaceous layer: *Cyclamen* spp..Parent material: limestone. **Soil** (Soil Survey Staff, 2014): fine, mixed, mesic Typic Humustept.

OLn	8-6	2-3	-	-	-	0	cw	5	Light wild boar turbation. Undecomposed leaves and branch fragments of *Q. cerris*, *F. ornus, R. aculeatus*, *C. sanguinea*
OLv	6-3	1-4	-	-	-	0	cw	5	Light wild boar turbation. Undecomposed leaves and branch fragments of *Q. cerris*, *F. ornus, R. aculeatus*, *C. sanguinea*. Abundant mesofauna
OH	3-0	0.5-4	7.5YR 3/2	-	-	1mi,vf,f	cw	5	Light wild boar turbation. A few mycelium
A	0-2	2-3	7.5YR 2.5/1	2f,m sbk	fr	2mi,vf,f	cw	10	Charcoal fragments. A few mycelium
Bw1	2-29	25-29	10YR 4/6	2f,m,c abk-sbk	fr	1mi,vf; 2f; 1m,c	cw	10	A few thin cutans
Bw2	29-61	32-34	10YR 4/4	2-3f,m sbk	fr	1mi,vf,f; 2m,c	cw	30	A few to common thin cutans
R	61-65+	-	-	-	-	-	-	-	

Plot 6. (43.21002N, 10.70252E) Slope 10-13%; Exposure: NNW; Altitude: 339-343 m – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm.
Emerging rock: 10%. Soil cover: 90%. Understorey cover: 70%. Moss cover: 5%. Vegetation. Trees: *Quercus cerris* L. (90%), *Fraxinus ornus* L, *Ulmus* spp., *Ostrya carpinifolia* Scop., *Quercus ilex* L. Bushes: *Ruscus aculeatus* L.(60%), *Cornus sanguinea* L, *Crataegus monogyna* Jacq., *Smilax aspera* L., *Rubus ulmifolius* Schott., *Daphne laureola* L., *Hedera helix* L., *Pteridium aquilinum* (L.) Kunh. Herbaceous layer: *Cyclamen* spp. Parent material: limestone.
Soil (Soil Survey Staff, 2014): fine, mixed, mesic Typic Humustept.

OLn	7-3	2-6	-	-	-	0	cw	0	Undecomposed leaves and branch fragments

									of *Q. cerris, F. ornus, R. aculeatus*, *Q. ilex, C, sanguinea*
OLv	3-1	2-3	-	-	-	0	cw	0	Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, R. aculeatus*, *Q. ilex, C, sanguinea*
OH	1-0	0.5-1	7.5YR 3/2	-	-	1mi,vf	as	0	A few mycelium
A	0-3	1-3	7.5YR 3/1	2f,m sbk	fr	2mi,vf; 1f	cw	0	Charcoal fragments. A few mycelium
Bw1	3-16	10-13	10YR 5/4	2f,m abk	fr	2mi,vf,f,m	cs	0	A few mycelium. A few thin cutans
Bw2	16-86	60-70	10YR 5/6	2f,m abk-sbk	fr	2mi,vf; 3f,m,co	cs	0	Charcoal fragments. Common moderate cutans
Bg1	86-126	35-40	7.5YR 4/4	2f,m abk,sbk	fr	1mi,vf,f,m,co	cs	0	Abundant thick cutans
Bg2	126-155+	-	10YR 5/6	2f,m abk,sbk	fr	1mi,vf,f,m,co	-	0	Abundant thick cutans

Plot 9. (43.20682N, 10.70149E) Slope 15-18%; Exposure: NNE; Altitude: 339-344 m – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Emerging rock: 15%. Soil cover: 95%. Understorey cover: 50%. Moss cover: 5%. Vegetation. Trees: *Quercus cerris* L. (90%), *Fraxinus ornus* L., *Ulmus* spp., *Ostrya carpinifolia* Scop. Bushes: *Ruscus aculeatus* L. (60%), *Cornus sanguinea* L., *Crataegus monogyna* Jacq., *Smilax aspera* L., *Rubus ulmifolius* Schott, *Hedera helix* L., *Pteridium aquilinum* (L.) Kunh. Herbaceous layer: *Cyclamen* spp. Parent material: limestone.
Soil (Soil Survey Staff, 2014): fine, mixed, mesic Typic Humustept.

OLn	10-5	3-8	-	-	-	-	cw	10	Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, R. aculeatus*, *Q. ilex, C. sanguinea*. A few mycelium
OLv	5-3	2-5	-	-	-	0	cw	15	Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, R. aculeatus*, *Q. ilex, C. sanguinea*. Common mesofauna
OFr	3-2	3-4	-	-	-	0	cw	15	Common mycelium
OH	2-0	2-3	7.5YR 3/2	-	-	1mi,vf,f	cw	15	A few mycelium
A	0-3	7-10	10YR 3/2	3f cr	fr	3mi,vf,f; 1m	cw	0	A few mycelium
Bw1	3-11	15-25	7.5YR 4/4 10YR 5/4	3f,m sbk+cr	fr	1mi,vf; 2f; 1m	cw	3	A few thin cutans
Bw2	11-27	14-15	10YR 4/2 10YR 5/4	3f,m abk+sbk	fr	1mi,vf,f,m; 2co	cw	<1	Charcoal fragments. Common thin cutans
Bwb	27-48	18-20	10YR 5/6	3f,m abk-sbk	fr	1mi,vf; 3f; 2co	cw	60	Common thin cutans
BCb	48-56+	-	10YR 6/4	2f,m abk	fr	1mi,vf,f,m,co	-	60	A few to common thin cutans

Plot 10. (43.20783N, 10.70134E) Slope 7-12%; Exposure: N; Altitude: 340-343 m – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Emerging rock: 20%. Boulders: 5%. Soil cover: 90%. Understorey cover: 60%. Moss cover: 5%. Vegetation. Trees: *Quercus cerris* L.(90%), *Fraxinus ornus* L., *Ulmus* spp., *Ostrya carpinifolia* Scop. Bushes: *Ruscus aculeatus* L. (60%), *Cornus sanguinea* L., *Crataegus monogyna* Jacq., *Smilax aspera* L, *Rubus ulmifolius* Schott., *Hedera helix* L. Herbaceous layer: *Cyclamen* spp. Parent material: limestone.
Soil (Soil Survey Staff, 2014): fine, mixed, mesic Typic Humustept.

OLn	10-5	4-9	-	-	-	0	cw	20	Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, R. aculeatus*, *Q. ilex*, *C. sanguinea.* A few mycelium
OLv	5-3	2-6	-	-	-	0	cw	20	Undecomposed leaves and branch fragments of *Q. cerris, F. ornus, R. aculeatus*, *Q. ilex*, *C. sanguinea.* A few mycelium
OH	3-0	3-4	10YR 3/2	-	-	1mi	cw	20	A few mesofauna
A	0-3	3-4	7.5YR 2.5/1	3f cr	fr	2mi,vf,f	cw	1-2	Charcoal fragments. A few mesofauna
AB	3-8	4-6	10YR 4/4	3m abk+sbk	fr	2mi,vf	cw	1-2	Charcoal fragments. A few mycelium
Bw1	8-16	6-9	10YR 4/3	3m abk	fr	2mi,vf; 3f,m	cw	2-3	A few mycelium. A few thin cutans
Bw2	16-32	14-17	10YR 5/4	3f,m abk-sbk	fr	1mi,vf; 3f,m,c	cw	5	Charcoal fragments. Common thick cutans
Bwb	32-51	-	10YR 5/4	3f,m sbk	fr	1mi,vf; 3f; 2co	cw	60	A few moderate cutans
BCb	51-60+	-	10YR 6/3	2m abk	fr		-	60	

[a]designation according to Baize et al. (2008) for organic horizons, to Schoeneberger et al. (2012) for mineral horizons.
[b]moist and crushed, according to the Munsell Soil Color Charts.
[c]1=weak, 2=moderate, 3=strong; tn=thin, f=fine, m=medium, c=coarse; cr=crumble, pl=platy, abk=angular blocky, sbk=sub-angular blocky; fi=firm; m= moist; fr=friable; vfr=very friable; w=wet; ss=slightly sticky.
[d]fi=firm; m= moist; fr, friable; vfr=very friable; w=wet; ss=slightly sticky.
[e]0=absent, v_1=very few, 1=few, 2=plentiful, 3=abundant; mi=micro, vf=very fine, f=fine, m=medium, co=coarse.
[f]c=clear; g=gradual; d=diffuse; s=smooth; w=weavy; I=irregular; b=broken.
[g]thin=<0.5 mm; moderate=≈1 mm; thick=>1 mm.

References

Soil Survey Staff, 2014. Keys to Soil Taxonomy, 12th edition. USDA–Natural Resources Conservation Service, Washington.

Table S2. Bulk density and contents of C and nutrients of fine earth in the soils under Turkey oak forest submitted to three management trials (control, moderate thinning and heavy thinning).

Trial	Profile	Horizon	Bulk density	TOC	TN	P_{av}	Ex. Ca	Ex. Mg	Ex. K
			g cm^{-3}	g kg^{-1}		mg kg^{-1}			
	2	OLn+OLv	0.35	355	13	43	n.a.	n.a.	n.a.
		OH	0.46	139	11	20	n.a.	n.a.	n.a.
		A	1.01	113	6	7	9800	280	244
		Bw1	1.35	12	1	3	2894	137	76
		Bw2	1.25	6	1	2	3410	103	70
	6	OLn+OLv	0.34	403	14	29	n.a.	n.a.	n.a.
		OH	0.36	304	15	26	n.a.	n.a.	n.a.
		A	0.98	161	8	11	6418	525	308
		Bw1	1.39	17	2	5	1481	187	47
		Bw2	1.31	9	1	3	1937	184	34
Control	9	OLn+OLv	0.31	409	14	43	n.a.	n.a.	n.a.
		OT+OH	0.59	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		A	1.03	107	7	2	6083	391	290
		Bw1	1.41	15	1	3	630	102	54
		Bw2	1.34	11	1	2	1864	165	72
		Bwb	1.28	13	1	0	4279	135	95
	10	OLn+OLv	0.32	390	14	41	n.a.	n.a.	n.a.
		OH	0.41	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		A	1.00	131	7	8	10484	413	599
		AB	1.34	35	2	0	1732	108	228
		Bw1	1.43	16	1	0	1384	168	582
		Bw2	1.39	13	1	0	3433	97	152
		Bwb	1.38	20	1	0	4334	60	95
Moderate thinning	1	OLn+OLv	0.31	412	13	33	n.a.	n.a.	n.a.
		OH	0.43	192	14	19	n.a.	n.a.	n.a.
		A	1.06	135	7	9	8055	403	333

		Bw1	1.31	18	1	1	2863	168	81
		Bw2	1.29	15	2	0	5230	93	93
		Bw3	1.29	10	2	0	4626	64	70
		OLn+OLv	0.38	274	11	31	n.a.	n.a.	n.a.
		OH	0.45	158	10	19	n.a.	n.a.	n.a.
		A	1.05	118	6	8	8361	258	206
	4	AB	1.44	12	1	5	4719	153	96
		Bw1	1.36	12	2	3	2688	85	44
		Bw2	1.36	7	1	1	2462	64	28
		OLn+OLv	0.33	371	12	40	n.a.	n.a.	n.a.
		OT+OH	0.39	255	13	30	n.a.	n.a.	n.a.
		A	1.01	146	8	8	2950	308	243
	8	Bw	1.49	11	0	0	356	61	38
		Bg1	1.22	8	1	0	1952	126	65
		Bg2	1.25	9	1	0	5068	127	88
		OLn+OLv	0.33	383	13	52	n.a.	n.a.	n.a.
		OH	0.40	240	14	39	n.a.	n.a.	n.a.
		A	0.96	148	8	17	4683	411	240
		AB	1.38	27	1	3	694	118	104
	12	Bw1	1.37	9	1	1	897	185	54
		Bw2	1.32	6	1	0	1349	186	54
		Bg	1.33	6	1	2	1697	218	50
		OLn+OLv	0.35	350	12	37	n.a.	n.a.	n.a.
		OH	0.43	196	11	24	n.a.	n.a.	n.a.
	3	A	1.07	203	9	25	11643	483	449
Heavy thinning		Bw1	1.29	24	2	2	4558	199	131
		Bw2	1.31	13	1	0	4388	124	63
	5	OLn+OLv	0.33	369	13	41	n.a.	n.a.	n.a.
		OH	0.44	166	11	23	n.a.	n.a.	n.a.

	A	0.99	141	6	15	7531	466	341
	Bw1	1.37	22	2	5	2988	173	60
	Bw2	1.37	14	2	3	3372	87	45
7	OLn+OLv	0.32	385	13	41	n.a.	n.a.	n.a.
	OH	0.45	169	10	21	n.a.	n.a.	n.a.
	A	0.98	112	7	15	8471	400	329
	Bw	1.44	18	1	0	1788	149	94
	Bg1	1.46	9	1	2	3210	191	101
	Bg2	1.26	8	1	0	3620	158	96
11	OLn+OLv	0.32	417	15	45	n.a.	n.a.	n.a.
	OT+OH	0.40	218	12	32	n.a.	n.a.	n.a.
	A	0.87	132	4	21	5478	810	412
	Bw1	1.47	14	1	1	137	69	159
	Bw2	1.37	6	1	0	1834	204	122

Table S3. Bulk density and contents of C and nutrients of skeleton in the soils under Turkey oak forest submitted to three management trials (control, moderate thinning and heavy thinning).

Trial	Bulk density	TOC	TN	P_{av}	Ex. Ca	Ex. Mg	Ex. K
	g cm^{-3}	g kg^{-1}		mg kg^{-1}			
Control	2.59	$3.12 \cdot 10^{-3}$	$4.05 \cdot 10^{-5}$	0	4759	541	27
Moderate thinning	2.11	$4.87 \cdot 10^{-3}$	$5.02 \cdot 10^{-5}$	0	3365	567	19
Heavy thinning	2.18	$3.35 \cdot 10^{-3}$	$3.98 \cdot 10^{-5}$	0	5127	395	14

The parameters were measured on a composite sample made by skeleton subsamples taken from all the profiles of each management trial.

Table S4. Stocks of C and nutrients both in the fine earth (FE) and in the skeleton (SK) fractions, for each genetic horizon of the soils under Turkey oak L.forest submitted to three management trials (control, moderate thinning and heavy thinning). Natural Reserve of Monterufoli-Caselli forest.

Trial	Profile	Horizon	FE	SK	C stock FE	C stock SK	N stock FE	N stock SK	P stock FE	P stock SK	Mg stock FE	Mg stock SK	K stock FE	K stock SK	Ca stock FE	Ca stock SK
			%		T ha^{-1}				Kg ha^{-1}							
		OLn+OLv	95	5	61.45	0.0004	2.17	0.00005	7.51	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OH	95	5	19.32	0.0003	1.46	0.00003	2.80	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	2	A	90	10	22.86	0.0002	1.17	0.00002	1.33	0.00	56.56	0.23	49.29	0.01	1979.60	2.03
		Bw1	90	10	44.46	0.0023	4.75	0.00027	9.11	0.00	499.37	3.11	277.02	0.13	10548.63	27.43
		Bw2	70	30	25.33	0.0028	5.96	0.00032	7.20	0.00	412.00	3.69	280.00	0.15	13640.00	32.51
		OLn+OLv	100	0	81.87	0.0000	2.88	0.00000	5.86	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OH	100	0	11.06	0.0000	0.55	0.00000	0.95	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	6	A	100	0	47.31	0.0000	2.24	0.00000	3.32	0.00	154.35	0.00	90.55	0.00	1886.89	0.00
Control		Bw1	100	0	31.09	0.0000	3.29	0.00000	8.67	0.00	337.91	0.00	84.93	0.00	2676.17	0.00
		Bw2	100	0	85.70	0.0000	10.95	0.00000	22.93	0.00	1687.28	0.00	311.78	0.00	17762.29	0.00
		OLn+OLv	90	10	88.30	0.0006	3.05	0.00007	9.18	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		A	100	0	33.13	0.0000	2.21	0.00000	0.53	0.00	120.82	0.00	89.61	0.00	1879.65	0.00
	9	Bw1	97	3	17.27	0.0007	0.96	0.00008	3.72	0.00	115.06	0.92	60.91	0.04	710.64	8.13
		Bw2	99	1	23.62	0.0014	2.11	0.00016	3.43	0.00	353.76	1.84	154.37	0.08	3996.42	16.26
		Bw3	99	1	33.73	0.0017	2.64	0.00020	0.08	0.00	345.60	2.30	243.20	0.09	10954.24	20.32
	10	OLn+OLv	80	20	87.67	0.0006	3.18	0.00007	9.23	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		A	80	20	39.27	0.0003	1.95	0.00003	2.43	0.00	123.90	0.35	179.70	0.01	3145.20	3.05

		AB	98	2	23.50	0.0004	1.34	0.00005	0.02	0.00	72.36	0.58	152.76	0.02	1160.44	5.08
		Bw1	98	2	18.11	0.0007	0.95	0.00008	0.03	0.00	192.19	0.92	665.81	0.04	1583.30	8.13
		Bw2	97	3	28.24	0.0014	1.99	0.00016	0.07	0.00	215.73	1.84	338.05	0.08	7634.99	16.26
		Bw3	40	60	52.44	0.0017	2.67	0.00019	0.08	0.00	157.32	2.19	249.09	0.09	11363.75	19.30
Moderate thinning	1	OLn+OLv	70	30	51.74	0.00035	1.69	0.00004	4.11	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OH	70	30	16.53	0.0002	1.17	0.00002	1.62	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		A	70	30	28.54	0.0002	1.44	0.00002	1.82	0.00	85.44	0.23	70.60	0.01	1707.66	2.03
		Bw1	80	20	55.48	0.0020	3.96	0.00023	3.92	0.00	506.18	2.65	244.05	0.11	8626.22	23.37
		Bw2	80	20	17.21	0.0008	2.42	0.00009	0.03	0.00	107.97	1.04	107.97	0.04	6072.03	9.14
		Bw3	70	30	58.75	0.0040	9.34	0.00046	0.18	0.00	379.78	5.30	415.38	0.22	27450.68	46.73
	4	OLn+OLv	80	20	51.78	0.0004	2.06	0.00005	5.79	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OH	80	20	7.08	0.0001	0.45	0.00001	0.86	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		A	95	5	24.74	0.0002	1.22	0.00002	1.58	0.00	54.18	0.23	43.26	0.01	1755.81	2.03
		AB	95	5	26.56	0.0013	3.04	0.00015	10.80	0.00	330.48	1.73	207.36	0.07	10193.04	15.24
		Bw1	95	5	43.74	0.0023	5.31	0.00026	9.90	0.00	300.56	3.00	155.58	0.12	9504.77	26.42
		Bw2	95	5	17.72	0.0017	3.15	0.00019	3.36	0.00	165.38	2.19	72.35	0.09	6361.81	19.30
	8	OLn+OLv	90	10	73.45	0.0005	2.40	0.00006	7.91	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OT+OH	90	10	40.21	0.0003	2.12	0.00004	4.71	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		A	99	1	29.56	0.0002	1.71	0.00002	1.52	0.00	62.22	0.23	49.09	0.01	595.90	2.03
		Bw	99	1	30.23	0.0016	0.98	0.00018	0.08	0.00	163.60	2.07	101.92	0.08	954.79	18.29
		Bg1	99	1	17.49	0.0017	1.99	0.00019	0.07	0.00	292.07	2.19	150.67	0.09	4524.74	19.30
		Bg2	99	1	30.66	0.0024	3.82	0.00028	0.11	0.00	444.50	3.23	308.00	0.13	17738.00	28.45

		OLn+OLv	95	5	88.64	0.0006	3.03	0.00007	12.11	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OH	95	5	19.03	0.0002	1.12	0.00002	3.08	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		A	100	0	56.96	0.0000	2.92	0.00000	6.41	0.00	157.82	0.46	92.16	0.02	1798.27	4.06
	12	AB	100	0	18.60	0.0000	0.82	0.00000	1.79	0.00	81.42	0.58	71.76	0.02	478.86	5.08
		Bw1	100	0	27.48	0.0000	1.73	0.00000	3.47	0.00	582.94	2.65	170.15	0.11	2826.45	23.37
		Bw2	100	0	16.10	0.0000	1.56	0.00000	0.09	0.00	540.14	2.53	156.82	0.10	3917.50	22.35
		Bg	100	0	34.91	0.0000	3.33	0.00000	9.15	0.00	1246.74	4.95	285.95	0.20	9705.14	43.69
		OLn+OLv	95	5	48.85	0.0003	1.73	0.00004	5.16	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OH	95	5	16.75	0.0002	0.93	0.00002	2.09	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	3	A	99	1	43.48	0.0002	1.93	0.00002	5.29	0.00	103.36	0.23	96.09	0.01	2491.60	2.03
		Bw1	99	1	31.31	0.0009	2.29	0.00010	2.06	0.00	256.71	1.15	168.99	0.05	5879.82	10.16
		Bw2	99	1	30.72	0.0016	3.53	0.00018	0.07	0.00	292.39	2.07	148.55	0.08	10346.90	18.29
		OLn+OLv	85	15	72.59	0.0005	2.62	0.00006	8.08	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OH	85	15	7.28	0.0001	0.49	0.00001	1.01	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Heavy thinning	5	A	80	20	27.84	0.0002	1.24	0.00002	2.95	0.00	92.27	0.23	67.52	0.01	1491.14	2.03
		Bw1	80	20	48.13	0.0014	3.53	0.00016	10.74	0.00	379.22	1.84	131.52	0.08	6549.70	16.26
		Bw2	80	20	74.78	0.0034	8.75	0.00039	16.03	0.00	464.84	4.49	240.44	0.18	18016.60	39.62
		OLn+OLv	95	5	61.46	0.0004	2.00	0.00005	6.59	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OH1	95	5	22.79	0.0003	1.35	0.00003	2.79	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	7	OH2	95	5	0.00	0.0002	0.00	0.00002	0.00	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		A	90	10	22.03	0.0002	1.35	0.00002	2.88	0.00	78.40	0.23	64.48	0.01	1660.32	2.03
		Bw	98	2	39.46	0.0013	2.36	0.00015	0.06	0.00	321.84	1.73	203.04	0.07	3862.08	15.24

	Bg1	99	1	31.40	0.0021	3.59	0.00024	6.83	0.00	669.26	2.76	353.90	0.11	11247.84	24.38
	Bg2	99	1	26.55	0.0024	2.82	0.00028	0.11	0.00	557.42	3.23	338.69	0.13	12771.36	28.45
11	OLn+OLv	90	10	79.53	0.0005	2.94	0.00006	8.56	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

CHAPTER 3 - IMPACT OF THE MANAGEMENT ON THE SOIL ORGANIC C AND NUTRIENTS (N, P, Ca, Mg, K) STORAGE CAPACITY IN FORESTS WITH SOILS DEVELOPED ON DIFFERENT PARENT MATERIALS

ELSEVIER

Journal of Environmental Management
Volume 330, 15 March 2023, 117181

Research article

Holm oak (*Quercus ilex* L.) cover: A key soil-forming force in controlling C and nutrient stocks in long-time coppice-managed forests

Lorenzo Camponi [a], Valeria Cardelli [a], Stefania Cocco [a], Dominique Serrani [a], Andrea Salvucci [a], Andrea Cutini [b], Alberto Agnelli [c, d], Gianfranco Fabbio [b], Giada Bertini [b], Pier Paolo Roggero [e], David C. Weindorf [f], Giuseppe Corti [a, g]

Show more

https://doi.org/10.1016/j.jenvman.2022.117181

Holm oak (*Quercus ilex* L.) cover: A key soil-forming force in controlling C and nutrient stocks in long-time coppice-managed forests

Lorenzo Camponi[a], Valeria Cardelli[a]*, Stefania Cocco[a], Dominique Serrani[a], Andrea Salvucci[a], Andrea Cutini[b], Alberto Agnelli[c,d], Gianfranco Fabbio[b], Giada Bertini[b], Pier Paolo Roggero[e], David C. Weindorf[f], Giuseppe Corti[a,g]

[a] Department of Agricultural, Food and Environmental Sciences, Polytechnic University of Marche, Ancona, Italy

[b] CREA Research Centre for Forestry and Wood, Arezzo, Italy

[c] Department of Agricultural, Food and Environmental Sciences, University of Perugia, Perugia, Italy

[d] Research Institute on Terrestrial Ecosystems (IRET-CNR), Sesto Fiorentino, Italy

[e] Department of Agricultural Sciences, University of Sassari, Sassari, Italy

[f] Department of Earth and Atmospheric Sciences, Central Michigan University, Mount Pleasant, MI, USA

[g] CREA Research Centre for Agriculture and Environment, Rome, Italy

*Correspondence: v.cardelli@staff.univpm.it

Abstract

In forest ecosystems, soil-plant interactions drive the physical, chemical, and biological soil properties and, through soil organic matter cycling, control the dynamics of nutrient cycles. Parent material also plays a fundamental role in determining soil's chemical properties and nutrient availability. In this study, eight long-time coppice-managed Holm oak forests under conversion to high forest, located under similar climatic conditions in Tuscany and Sardinia Regions (Italy), and grown on soils developed from three different lithologies (limestone, biotite granite, and granite with quartz veins) were evaluated. The research aimed to a) estimate the amount of C and nutrients (total N and potentially available P, Ca, Mg, and K) stored both in the organic, organo-mineral, and mineral horizons and at fixed depth intervals (0-0.3 and 0.3-0.5 m), and b) assess the dominant pedological variables driving elemental accumulation. The soils were described and sampled by genetic horizons and each sample was analyzed for its C and nutrient concentration in both the fine earth and skeleton fractions. Despite the different parent materials from which the soils had evolved, the physicochemical properties and the C and nutrient stocks for the 0-0.3 and 0.3-0.5 m layers did not show substantial differences among the eight soils. Conversely, some differences were observed in the stocks of potentially available P and Ca *per* 0.01 m of mineral horizons. The findings show that over time, plant-induced pedogenic processes (acidification, mineral weathering, organic matter addition, and nutrient cycling) almost obliterated the influence of parent materials on soil properties. This resulted in the upper soil horizons that showed similar characteristics, even though derived from different lithologies. However, among the study sites, some differences occurred due to lithology, as in the case of the soils derived from calcareous parent materials that had high concentrations of exchangeable Ca in the mineral horizons and, likely, to environmental variables (e.g., exposure), which possibly influenced litter degradation and the release of nutrients such as N and available P.

Keywords: forest soil, soil organic matter, soil horizons, parent material, forest management

1. Introduction

In forest environments, a complex and intimate relationship exists between plants and soil that occurs through interactions among root activity, canopy coverage, and litter production and quality that lead to different physical, chemical, and biological soil properties (Agnelli et al., 2016; De Feudis et al., 2019). Concurrently, the degradation of organic matter by the soil microbial community ensures that nutrients are available for plant growth (He et al., 2020). In this web of interactions, parent material plays a key role in determining the soil's chemical and biochemical properties (Cardelli et al., 2017). The nature of the parent material affects pH, texture, and nutrient supply and induces distinct levels of soil fertility which subsequently influence the composition and abundance of vegetation (Skorupa et al., 2017) and the amount and quality of soil organic matter from litter input (Brock et al., 2019).

The current stock of C in the world's forest soils (0-1 m thickness) is estimated to be 383 ± 30 Pg C (Pan et al., 2011), 44% of the total C stocked by forest ecosystems. However, its value may vary depending on the methodology used for estimation (De Feudis et al., 2022) which could be improved by accounting for the C pool of the soil rock fragments (Agnelli et al., 2002; Corti et al., 2002). Concurrently, organic C cycling and storage in forest soils drive ecosystem functionality, mitigate climate change, and contribute to forest sustainability (Cutini et al., 2021). The relevance of soil C is also due to its robust link with N and P cycles (Innangi et al., 2017; Vindušková et al. 2019). Indeed, organic C mineralization is controlled by N and P availability and their stoichiometric ratios because of their key role in regulating the abundance and activity of the soil microbial community (Kirkby et al., 2013; Zheng et al., 2021). While N in the terrestrial ecosystem comes from atmospheric N_2 fixation and the soil N, mostly in organic form, becomes available to living organisms via decomposition and mineralization of organic matter by soil microbial community (Alarcón-Gutiérrez et al., 2008; Marco et al., 2016), the main source of soil P is rock weathering (Walker and Syers, 1976). The inorganic P derived from the weathering of parent rock can precipitate as phosphatic salts with very low solubility, be strongly bound to reactive secondary minerals, and be immobilized in organic forms (Arenberg and Arai, 2019). Several authors (e.g., Bünemann et al., 2016; Brödlin et al., 2019) reported that in forest ecosystems the mineralization of organic matter is the main source of N and P, especially in the organic and organo-mineral horizons (O and A horizons, respectively). In the mineral horizons, the differential sorption of inorganic N and P may result in their availability to plants becoming imbalanced (Brödlin et al., 2019).

Although C, N, and P are important to forest functionality (e.g., Marco et al., 2016; Innangi et al., 2017), information on the soil-forming factor(s) involved in C, N, and P accumulation in forest soils of the Mediterranean basin, especially under Holm oak (*Quercus ilex* L.) forests, is scarce. Holm oak forests represent 4.4% of the woodlands of the Mediterranean region and are adapted to a wide range of pedoclimatic conditions (e.g., Alarcón-Gutiérrez et al., 2008; Gimeno et al., 2009; FAO, 2019; Vacca et al., 2018). In Italy, Holm oak forests account for 7.2% of high forests (CFS and CRA-MPF, 2005), are mostly in pure stands, and are generally managed by coppicing. Reduced use of wood biomass as fuel during the past 50 years (Unrau et al., 2018) has generally resulted in their conversion to high forests (CFS and CRA-MPF, 2005). This evergreen broadleaved oak is highly adaptable and, since its habitat is in an old and massively populated part of the world, most Holm oak forests have been subjected to intensive management and anthropic disturbances that have modified the soil-vegetation system (Carrari et al., 2017; Pulido et al., 2001; González et al., 2012) and, consequently, their capability to stock C, N, and P into the soil.

Given the abovementioned observations, this research assesses the influence of soil-forming factor(s) in eight Holm oak forests on the accumulation of C and nutrients in the soil. The selected forests had similar management histories (stored coppices in conversion to high forest) but grew on soils developed from three different parent materials and were located in three Italian locations of the northernmost range of the species. The aims of the study were to: 1) estimate the amount of C and nutrients (total N and potentially available P, Ca, Mg, and K) stored in the litter layer and in two depth intervals (0-0.3 and 0.3-0.5 m) within the mineral soil and, 2) appraise the variability of these stocks to assess the dominant pedogenic variable driving the elemental accumulation. We hypothesize that, because of the potential influence of the parent material in the pedogenetic processes, differences of soil C and nutrients stocks occur among the tree sites.

2. Materials and methods

2.1. Study sites

Eight study sites within three long-time coppice-managed forests (Fantini et al., 2020) with Holm oak as the dominant tree species were selected in two Italian regions, Tuscany and Sardinia (Figure 1). All the forests were coppiced during conversion to high forest. The soils under the three forests had developed on different parent materials. Detailed information on the eight study sites is reported in Table S1 of Supplementary Materials and are summarized here below.

Three sites (Alberese, Poggio ai Lecci, and Albatraia) were selected within the Maremma Natural Park (total area 8,902 ha), on the southern Tuscan coast (Italy). These study sites were located between 133 and 387 m above sea level (a.s.l.), with a dominant exposure between NNW and W and a steep slope between 15 and 25%. In all the areas there were signs of intense erosion, which could have been partly favoured by the turning activity of wild boars and by the discharge of the stemflow solution that produced rills originating at the base of the stems. The mean annual air temperature (MAAT) ranged from 13.3 and 14.3 °C and the mean annual precipitation (MAP) from 630 to 658 mm. According to the Köppen Classification (Peel et al., 2007), the sites were submitted to a Hot-Summer Mediterranean climate (Csa). The stand, aged 74 years, was characterized by a mean of 1805 trees ha^{-1}, a basal area of 32 m^2 ha^{-1}, a mean tree diameter at breast height (Dbh) of 0.16 m, a mean tree height of 13 m, and a dominant height of 17 m. The soils had developed on calcareous parent materials that were represented by massive limestone with veins of calcite and flintstone at Alberese, calcareous sandstone interbedded with yellowish schistose marls with a small presence of anagenite and limestone at Poggio ai Lecci, limestone with flintstone veins and a small presence of anagenite at Albatraia. All the soils were very skeletal.

Three sites (Is Cannoneris 1, Is Cannoneris 2, and Is Cannoneris 3) were selected within the Is Cannoneris Regional property forest (total area 4,800 ha) located in the southern part of Sardinia (Italy). The three study sites were between 905 and 915 m a.s.l., with a dominant exposure between SSE and E and two main slopes, one of 15-20% (Is Cannoneris 1 and 2) and the other of 30-40% (Is Cannoneris 3). Despite the steep slope, soil erosion was generally low, while the disturbance caused by wild boar rooting activity was intense. The MAAT was 12.3 C° and the MAP was ≈615 mm. According to the Köppen Classification (Peel et al., 2007), the sites were submitted to a Hot-Summer Mediterranean climate (Csa). The stand, aged 62 years, showed an average of 2200 trees ha^{-1}, a basal area of 31 m^2 ha^{-1}, a mean tree Dbh of 0.16 m, a mean tree height of 12 m, and a dominant height of 13 m. The soils had developed on biotite granite and were poorly skeletal.

Two sites (Sette Fratelli 1 and Sette Fratelli 2) were selected within the Sette Fratelli Regional Natural Park (total area 9,887 ha) located in the South-Western part of Sardinia (Italy). The two study sites were between 760 and 778 m a.s.l., with a dominant exposure between SW and E and a gentle slope (about 5%). Due to the gentle slope of the area, soil erosion was low. MAAT and MAP were 12.5 C° and ≈695 mm, respectively. According to the Köppen Classification (Peel et al., 2007), the sites were submitted to a Hot-Summer Mediterranean climate (Csa), The stand, aged 69 years, had an average of 2314 trees ha^{-1}, a basal area of 42 m^2 ha^{-1}, a mean tree Dbh of 0.16 m, a mean tree height of 12 m, and a dominant height of 16 m. The soils had developed on granite with quartz and pegmatite veins and were very skeletal.

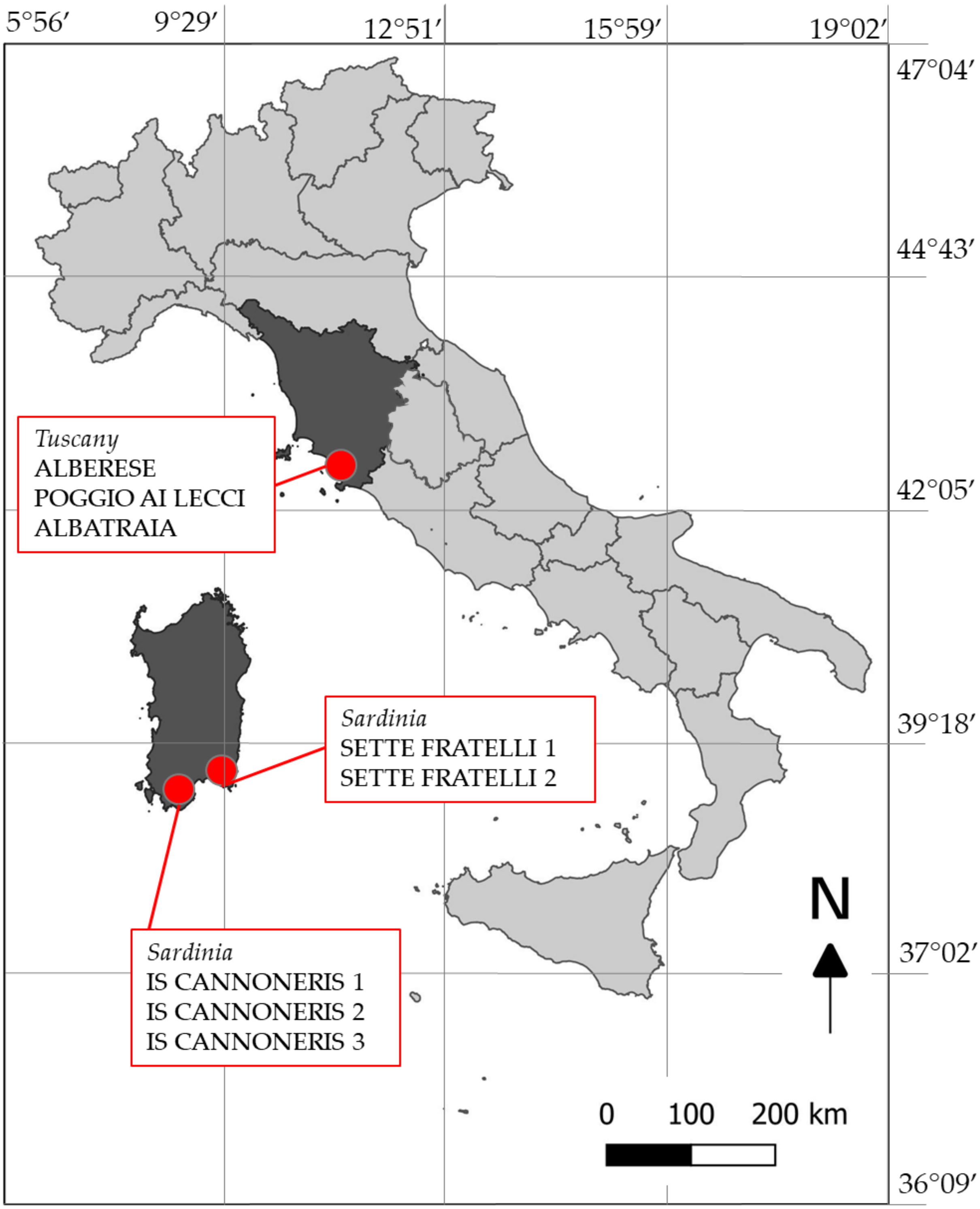


Fig. 1. Study sites location in Tuscany and Sardinia regions, Italy.

2.2 Soil trenching, morphological description, sampling, analysis

At each study site, soil profiles were exposed in areas that varied according to the topography: *i*) in the sites of Alberese, Poggio ai Lecci, and Albatraia the profiles were located in areas of 600 to

1000 m^2; *ii*) in the Is Cannoneris sites the study areas ranged from 800 m^2 for that on the steeper slope, and from 1000 to 1200 m^2 for those on the gentler slopes; *iii*) in the Sette Fratelli sites the study areas ranged from 1500 to 2000 m^2.

Following the protocol reported by Camponi et al. (2022), each soil profile was dug at about 1 m downslope from the stem of one of the oldest trees present in the sampling area and until the lithic contact or the depth of ≈1 m. The organic horizons were morphologically described according to Baize et al. (2008) and sampled in an area of about 3-4 m^2 around each profile. The morphology of the organo-mineral and mineral horizons, together with their content of cobbles and stones, were described by Schoeneberger et al. (2012). Soil morphologies together with general information about the areas are reported in Table S1 of Supplementary Materials.

Soil samples (≈3 kg) were collected by genetic horizons. At the time of sampling, two horizontal soil cores per each horizon were taken by steel cylinders of 503 cm^3 (diameter 7.7 cm, height 10.8 cm) for the soil bulk density determination. For the organic horizons, the bulk density was estimated by pedotransfer functions (De Nicola et al., 2014). All collected samples were stored in a refrigerated bag during the field operations and, once in the laboratory, they were allowed to air-dry. Both mineral samples and soil cores were then sieved at 2 mm to separate the fine earth (< 2 mm fraction) from the skeleton (> 2-mm fraction).

The particle-size distribution was determined by the pipette method (Gee and Or, 2002), and pH was determined potentiometrically in water (1:2.5 v:v) (Cardelli et al., 2019). Total organic carbon (TOC) concentration was estimated by the Walkley-Black method (Nelson and Sommers, 1996), while the contents of total N (TN) was determined by dry combustion analyser (EA-1110, Carlo Erba Instruments, Milan, Italy). Potentially available P (P_{av}) was estimated by the Olsen method (Olsen, 1954). Potentially available Ca (Ca_{av}), Mg (Mg_{av}), and K (K_{av}) were displaced by a 0.2 M $BaCl_2$ solution (solid:liquid ratio 1:10) (Corti et al., 1997) and analyzed with a Shimadzu AA-6300 spectrophotometer (Tokyo, Japan). Methodologies are detailed in Points 1 and 2 of Supplementary Materials.

2.3 Data treatment, stock calculation, and statistical analysis

Because of the soil variability, profiles showed differences in the sequence of horizons. Thus, genetic horizons were grouped into soil tiers based on their nature: *i*) organic (O) tiers, made of well-expressed OL (OLn, OLv, OLt) and OH horizons, and of a mix of them (OLn/OLv, OLt/OH, and OLn/OLv/A); *ii*) organo-mineral (OM) tiers, grouping A, AB, E and EB horizons; and *iii*) mineral (M) tiers, formed by BA, Bw, BC, C&B, and C horizons (Table 1). The properties of the soil tiers were obtained by calculating the weighted mean of each property based on the mean thickness of each horizon. The element stocks for the 0-0.3 and 0.3-0.5 m of soil depth intervals were calculated considering the thicknesses of each genetic horizon, while the storage capacity per 0.01 m of each tier were obtained from the stocks of each horizon forming the tier itself, as described in Point 2 of Supplementary Materials. The differences among samples were tested by one-way analysis of variance (ANOVA) with R software, after checking the normality of the residual and homoscedasticity of the dataset by the Shapiro-Wilk statistical test and Levene's test at a 5% of significance level, respectively. Assumptions were not violated and Tukey's Honest Significant Difference (HSD) test with $P \leq 0.05$ was used to compare differences among means.

Table 1. Average morphological properties of the soil profiles under Holm oak (*Quercus ilex* L.) forests on three different parent materials (calcareous, biotite granite, granite with quartzite), according to each soil tier. Tuscany and Sardinia, Italy. For symbols see legend.

Tier	Horizons[a]	Depth[b]	Thickness[c]	Colour[d]	Structure[e]	Consistence[f]	Roots[g]	Boundary[h]	Skeleton[i]	Other observations
		m	m						%	
Site location: Alberese, Poggio ai Lecci, and Albatraia *Parent material: Calcareous; mean slope: 15-25 %; exposure: from NNW to W; average soil cover 60 %*										
Litter	OL; OLn; OLv; OH	0.04/0.02-0	0.02-0.04	- 5YR 3/2	-	-	0	cw cb ab	40-60	Evident boar activity signs; charcoal kilns; undecomposed leaves and little branches
Organo-mineral	A; AB	0-0.08/0.04	0.04-0.08	5YR 3/1 7.5YR 2.5/2	3f cr 1-3f m cr+sbk	fr fi	2mi,vf,f,m 3mi,vf,f,m,co	cw aw	40-60	Mycelium
Mineral	BA; Bw; BC; C; C&B	0.08/0.04-0.35/0.65+	0.27-0.60	5YR 4/6 10YR 7/3	3m c abk-sbk 1m abk	fr fi	2mi,vf,f; 3mco 2mi,vf,f,m,co	cw sw	10-70	Mycelium; altered rock fragments; nuciform structure
Site location: Is Cannoneris *Parent material: Biotite granite; mean slope: 17-35 %; exposure: from SSE to E; average soil cover 65 %*										
Litter	OLt; OH; OLn/OLv; OLt/OH	0.08/0.06-0	0.06-0.08	10YR 6/3 5YR 2.5/1	v1f m sbk-abk 1f cr	- vfr	0 1mi,vf,f	cw cb	10-15	Boar activity signs; undecomposed leaves, acorns, and little branches; mesofauna; mycelium
Organo-mineral	A; AB; E; EB	0-0.02/0.07	0.02-0.07	10YR 2/2 7.5YR 4/6	3f m gr sbk-abk 1-2 f,m cr-sbk	fr	2mi,vf, f 3mi,vf,f; 1m	cw cb	10-25	Mesofauna; mycelium
Mineral	Bw; BC; C	0.02/0.07-0.65/1.12+	0.58-1.00	7.5YR 4/4 10YR 5/6	- 3f m sbk-abk	fr	1mi,vf,m,co 2mi,vf; 3f, m, co	cw cb	25-95	Mesofauna, micelyum
Site location: Sette Fratelli *Parent material: Granite with quartzite; mean slope: 5 %; exposure: from SW to E; average soil cover 100 %*										

Litter	OLn/OLv/ A; OLt/OH; OLt	0.04/0.03-0	0.03-0.04	7.5YR 2.5/1 7.5YR 2.5/2	-	-	0	cw	60	Evident boar activity signs; charcoal kilns; undecomposed leaves, acorns, and little branches; mesofauna
Organo-mineral	A; EB	0-0.02/0.08	0.02-0.08	7.5YR 2.5/2 10YR 4/3	2f m sbk 3f sbk-abk	fr	1mi,vf; 1f 2mi,vf,f; 1m; 3co	cw	20-60	Mycelium
Mineral	Bw; BC; C	0.02/0.08-0.75/0.80+	0.64-0.72	7.5YR 3/4 10YR 4/6 7.5YR 5/4	1m abk 3f m abk	fr	1mi,vf,f,co 2mi,vf; 3f,m,co	cw	25-95	-

[a] Horizons: designation according to Baize et al. (2008) for organic horizons, to Schoeneberger et al. (2012) for mineral horizons.
[b] Depth: numbers separated by slash (/) indicate the range of depths observed in the profiles, while the hyphen (-) means "from (what is before it) to (what is after it)".
[c] Thickness: referred to the lowest and highest mean thickness.
[d] Colour: moist and crushed, according to the Munsell Soil Color Charts. The reported colours are the extremes for the horizons considered.
[e] Structure: 1=weak, 2=moderate, 3=strong; th=thin, f=fine, m=medium, c=coarse; cr=crumb, abk=angular blocky, sbk=sub-angular blocky, pl=platy. The reported structures are the extremes for the horizons considered.
[f] Consistence: fr=friable, fi=firm.
[g] Roots: 0=absent, v_1=very few, 1=few, 2=plentiful, 3=abundant; mi=micro, vf=very fine, f=fine, m=medium, co=coarse. The reported roots abundances are the extremes for the horizons considered.
[h] Boundary: a=abrupt, c=clear; g=gradual; d=diffuse; s=smooth; w=weavy; i=irregular; b=broken.
[i] Skeleton: by sight, according to the "percent of area covered" tables reported in Schoeneberger et al. (2012). The reported values are the extremes for the horizons considered.

3. Results

3.1 Site and soil properties

The Holm oak forests selected for this study were subjected to two main soil disturbances, one natural represented by wild boar activity and one of anthropogenic nature due to the past forest exploitation for firewood and charcoal production (Table 1 and Table S1 of Supplementary Materials).

The soils developed on calcareous parent materials (CA) (Alberese, Poggio ai Lecci, and Albatraia,) displayed a soil cover from 50 to 80% with abundant (40-60%) skeleton (cobbles and stones). The litter layer was poorly developed, with a thickness of 0.02-0.04 m; the organo-mineral and mineral horizons comprising the *solum* had an average thickness ranging from 0.04 to 0.08 m and from 0.27 to 0.60 m, respectively. The organo-mineral horizons showed a moderately to strongly developed granular to sub-angular blocky structure that became strongly developed angular and sub-angular blocky in the mineral horizons. Soil skeleton was abundant, amounting to >40% on average, and generally increased with depth.

At the sites on biotite granite bedrock (BG) (Is Cannoneris), the soil cover ranged from 55 to 75% and was partly due to rock fragments (pebbles and cobbles). A common feature of these areas was the presence of dead-standing trees of *Arbutus unedo* L.. The litter layer was relatively well developed with a thickness of 0.06-0.08 m; the thickness of the organo-mineral horizons ranged from 0.02 to 0.07 m, while that of the mineral horizons forming the *solum* was from 0.58 to 1.0 m. The soil structure consisted of strongly developed granular and sub-angular blocks in the organo-mineral horizons and strongly developed angular and sub-angular blocks in the mineral horizons. As a whole, the soil skeleton amounted to 10-95% and increased with depth.

The sites on granite with quartz veins bedrock (GQ) (Sette Fratelli) showed a soil surface covered by abundant (60%) rock fragments (cobbles and stones). In addition, there were many dead-standing trees of *Arbutus unedo* L. and remains of charcoal kilns. The litter layer was poorly developed with a thickness of 0.03-0.04 m; the organo-mineral horizons were 0.02 to 0.08 m thick and the mineral horizons had a thickness from 0.64 to 0.72 m. The organo-mineral horizons had a moderately to strongly developed sub-angular blocky structure, while the mineral horizons displayed a strongly developed angular and sub-angular blocky structure. Soil skeleton was abundant, on average amounting to 20-80%, generally increasing with depth.

3.2 Soil physicochemical properties and C and nutrient stocks

O, OM, and M tiers was moderate to slight acid reaction (pH values between 5.86 and 6.15), with differences among the three lithologies only for OM horizons (Table 2). As expected, soils developed on CA displayed slightly higher values than the other lithologies (row data, significances, and statistical F value are reported in Tables S2, S3, and S4a/b of Supplementary Materials). Considering the particle-size distribution of OM and M tiers, GQ soils had the highest sand content whereas BG soils and, to a lesser extent, CA soils had the largest silt content. These latter soils also showed the largest clay content in the M tier. Consequently, the texture classes of OM and M tiers were respectively sandy loam and clay loam for CA soils, and sandy loam and loamy sand for BG and GQ soils. In each group of soils, the O tier had the largest TOC, TN, and P_{av} contents, which decreased in the tiers below. Comparing the soil properties according to the different parent materials, the OM tier of CA soils had the largest TN content, while the M tier of GQ soils had a greater P_{av} content than that of CA and BG soils. TOC content did not differ significantly among the three lithologies (Table 2).

The stocks of elements in the litter and at fixed depth intervals (0-0.3 and 0.3-0.5 m) showed similar values among the three lithologies except for the P_{av} content in the litter (Table 3), which was the largest in BG soils and the lowest in CA soils. The contribution of the skeletons to the stocks was null for C, TN, and P_{av} but it ranged from ≈6 to ≈50 % for Ca_{av}, from ≈1 to ≈99 % for Mg_{av}, and from ≈1 to ≈96 % for K_{av} (Table S3).

When expressed per 0.01 m thickness, soils derived from the three parent materials did not show any difference in their capacity to store C and nutrients, with the exceptions of P_{av} and Ca_{av} in M tiers (Figure 2). Indeed, GQ soils showed a higher capacity to store P_{av} than CA and BG soils, while the largest amount of Ca_{av} was stored in CA soils. However, within each lithology, a different storage capacity occurred along the soil profiles. Although a constant decreasing trend occurred from organic to mineral tiers for the organic C stock in all three lithologies, the decreases in profile stocks of TN and P_{av} were less, especially for CA and GQ soils. The amount of Ca_{av} decreased toward the mineral horizons in CA and GQ soils, but it did not change with profile depth for BG soils. The 0.01-m stocks of Mg_{av} and K_{av} decreased from the OM to M tiers.

Table 2. Mean values of pH, particle-size distribution, and contents of total organic carbon (TOC), total nitrogen (TN), and potentially available phosphorus (P_{av}) of the organic, organo-mineral, and mineral tiers of the soils under Holm oak (*Quercus ilex* L.) stands developed from three different lithologies (calcareous, biotite granite, and granite with quartz veins). Tuscany and Sardinia, Italy. Numbers in parentheses are the standard deviations. Columns with different lowercase letters indicate differences among tiers within each soil, columns with different capital letters indicate differences among soils for the same tier, both at $P \leq 0.05$ level of significance.

Parent material	Tier	N	pH	Particle-size distribution			TOC	TN	P_{av}
				Sand	Silt	Clay			
				g kg^{-1}			g kg^{-1}		mg kg^{-1}
Calcareous (Alberese, Poggio ai Lecci, Albatraia)	Organic	5	6.09(0.25) ^{aA}	n.a.	n.a.	n.a.	383.31(104.87) ^{aA}	11.35(0.86) ^{aA}	15.87(2.77) ^{aA}
	Organo-Mineral	5	6.37 (0.50) ^{aA}	646(97) ^{aAB}	286(51) ^{bA}	69 (48) ^{bA}	101.62(19.59) ^{bA}	7.22(1.17) ^{bA}	11.30 (4.92) ^{aA}
	Mineral	9	5.98(1.51) ^{aA}	375(127) ^{bB}	333(27) ^{aB}	293(129) ^{aA}	20.02(14.13) ^{cA}	1.03(0.63) ^{cA}	1.22(0.76) ^{bB}
Biotite granite (Is Cannoneris)	Organic	8	5.82(0.24) ^{aA}	n.a.	n.a.	n.a.	276.53(108.43) ^{aA}	11.50(1.53) ^{aA}	20.18 (5.75) ^{aA}
	Organo-Mineral	6	5.72(0.38) ^{abB}	589(127) ^{aB}	316(98) ^{bA}	79(48) ^{bA}	72.69(25.74) ^{bA}	4.15(1.88) ^{bB}	7.69(7.61) ^{bA}
	Mineral	9	5.46(0.25) ^{bA}	418(27) ^{bB}	420(19) ^{aA}	163(20) ^{aB}	18.19(10.27) ^{cA}	1.02(0.48) ^{cA}	0.66 (0.44) ^{cB}
Granite with quarzite (Sette Fratelli)	Organic	4	6.13(0.18) ^{aA}	n.a.	n.a.	n.a.	215.80(152.06) ^{aA}	10.04(3.78) ^{aA}	19.67(7.88) ^{aA}
	Organo-Mineral	4	6.15(0.30) ^{aAB}	778(78) ^{aA}	169(50) ^{aB}	53(38) ^{bA}	70.71(26.52) ^{bA}	4.18(1.87) ^{bB}	11.12(6.25) ^{abA}
	Mineral	4	5.86 (0.67) ^{aA}	662(100) ^{aA}	192(66) ^{aC}	147(39) ^{aB}	33.16(33.49) ^{cA}	1.01(0.42) ^{cA}	2.47(1.98) ^{bA}

N is the number of genetic horizons grouped in the tier.
n.a. = not available data.

Table 3. Stocks of C, total N (TN), and potentially available P (P_{av}), Ca (Ca_{av}), Mg (Mg_{av}), and K (K_{av}) in the litter and in the layers 0-0.3 m and 0.3-0.5 m for the soils under Holm oak (*Quercus ilex* L.) stands developed from three different parent materials (calcareous, biotite granite, and granite with quartz veins). Tuscany and Sardinia, Italy. Numbers in parentheses are the standard deviations. Columns with different lowercase letters indicate differences among soil layers within each parent material, different capital letters indicate differences among parent materials for the same soil layer, both at $P \leq 0.05$ level of significance.

Parent material	Layer	Layer thickness	C	TN	P_{av}	Ca_{av}	Mg_{av}	K_{av}
		m	$Mg\ ha^{-1}$		$kg\ ha^{-1}$	$Mg\ ha^{-1}$		
Calcareous (Alberese, Poggio ai Lecci, Albatraia)	Litter	0.032(0.013) ^{A}	37.89(16.37) ^{aA}	1.11(0.57) ^{bA}	1.52(0.93) ^{aB}	n.a.	n.a.	n.a.
	0-0.3 m	-	66.06(26.52) ^{aA}	4.68(2.17) ^{aA}	5.67(2.23) ^{aA}	93.94(59.55) ^{aA}	7.02(3.86) ^{aA}	5.07(2.39) ^{aA}
	0.3-0.5 m	-	25.89(26.50) ^{aA}	1.07(0.85) ^{bA}	1.32(0.61) ^{aA}	53.25(52.80) ^{aA}	3.66(0.91) ^{aA}	1.43(0.17) ^{aA}
Biotite granite (Is Cannoneris)	Litter	0.064(0.029) ^{A}	97.20(47.25) ^{aA}	4.50(2.51) ^{abA}	6.84(3.34) ^{aA}	n.a.	n.a.	n.a.
	0-0.3 m	-	99.64(9.69) ^{aA}	5.49(0.38) ^{aA}	7.38(5.07) ^{aA}	30.06(15.96) ^{aA}	4.90(1.27) ^{aA}	3.83(1.08) ^{aA}
	0.3-0.5 m	-	27.72(5.22) ^{bA}	1.53(0.36) ^{bA}	0.91(0.28) ^{aA}	5.44(3.07) ^{aA}	2.43(1.00) ^{aA}	2.10(0.92) ^{aA}
Granite with quarzite (Sette Fratelli)	Litter	0.027 (0.015) ^{A}	33.38(23.08) ^{aA}	1.60(0.96) ^{bA}	3.18(1.86) ^{aAB}	n.a.	n.a.	n.a.
	0-0.3 m	-	108.34(27.77) ^{aA}	6.73(2.30) ^{aA}	16.02(7.03) ^{aA}	56.34(44.01) ^{aA}	6.81(3.31) ^{aA}	6.19(4.11) ^{aA}
	0.3-0.5 m	-	83.41(65.98) ^{aA}	2.07 (0.69) ^{abA}	5.59(5.58) ^{aA}	13.17(13.99) ^{aA}	3.36(0.82) ^{aA}	2.46(1.92) ^{aA}

n.a. = not available data

4. Discussion

4.1. Soil-forming forces drive soil properties and C and nutrient stock

Several authors have recognized that plants can influence soil properties like pH, organic carbon and N contents, and soil organic matter (SOM) composition, and enhance mineral weathering (e.g., by micorrhizal-roots exudates) through their biological activities (e.g., Sorenson et al., 2011; Adamczyk et al., 2016; 2019). However in the present study, soils displayed limited differences in terms of physicochemical properties, even though they originated from different parent materials. This similarity may be induced by the long time over which the Holm oak forests have covered these areas. The similar pH of soils derived from acid (BG, GQ) and alkaline (CA) parent rocks supports this view. Such a levelling of soil pH was possibly due to the long weathering processes faced by these soils, whose drivers were the accumulation of humus, the loss of basic cations through leaching and tree uptake, and the production of organic acids (Richter et al., 2007; Agnelli et al., 2016). Although CA soils should need a longer time or a higher weathering rate to reach a certain level of acidity when compared with soils developed from non-calcareous parent materials (Cocco et al., 2013), the high availability of nutrients and the consequent plant absorption may have promoted a heavy release of protons to counterbalance cation uptake (Neumann and Römheld, 2012). Further, according to Corti et al. (2019), throughfall and stemflow solutions produced by oak species are an important source of protons that contribute to soil weathering and carbonate dissolution in forest ecosystems. Even though slight differences in soil texture due to the nature of the parent materials occurred, all the soils showed an increase in clay content from the organo-mineral to the mineral horizons that may have been caused by illuviation processes. Since the occurrence of lessivage requires soil stability to produce an appreciable translocation of clay particles throughout the soil profile, the increase of clay content with depth could be interpreted as a further indication of the long period during which the forest land use has been maintained (Quénard et al., 2011; Calabrese et al., 2018).

The similar content of P_{av} in organic and organo-mineral horizons of soils developed from different lithologies again indicates the lengthy pedogenesis that occurred in the solum, thus diluting, or even obliterating, the influence of the parent materials on the soil properties. In general, soils derived from limestone are expected to have a lower P availability than those derived from acidic rocks like granite. This is because the alkaline pH and the high Ca concentration insolubilize phosphates (Penn and Camberato, 2019; Wilson et al., 2022). In the present study, the combined effect of slightly acid pH and large amounts of SOM in the upper horizons of the CA soils would have been counterbalanced to some extent by P precipitation as Ca-phosphate. At depth, the limited intensity of the pedogenic processes reduced P availability. In GQ soils, which had a higher P_{av} concentration than in CA and BG soils, P availability may have been influenced by the effect of other environmental variables (e.g., exposure) on SOM degradation (e.g., Scharenbroch et al., 2007; Egli et al., 2009; Cheng et al., 2021). In particular, the dominant SSE/SW facing forest soils on GQ would have increased the amount of solar radiation that reached the ground, fostering SOM mineralization with a consequent release of P in the mineral horizons. According to Egli et al. (2009), who reported a higher SOM degradation in alpine soils on south-facing rather than north-facing exposures, the north-facing exposure of CA soils fostered both SOM accumulation and higher TN concentration in the organo-mineral horizons. It was probably because of this that the P_{av} stock was higher in the litter of BG soils than in that of CA soils, while the values of the other stocks showed no difference among the lithologies due to the prolonged influence of Holm oak activity. The approach used in this study elucidated the important contribution of rock fragments to the stocks of soil elements that, for Caav, Mgav and Kav, ranged from ≈1 to ≈99% (Table S3 of Supplementary Materials). These results suggest that restricting soil chemical analyses to the fine earth fraction while concurrently discarding the skeletal fraction (Ugolini et al., 1996; Johnson and Turner, 2019), neglecting the contribution of the rock fragments and/or using the skeletal content as a diluent of the fine earth properties result in a significant underestimation of the soil's nutrient contents (Corti et al., 2002). Indeed, aside from those consisting solely of quartz, rock fragments may contain considerable amounts of nutrients and, depending on their lithology and degree of alteration, may represent a large reservoir of C, N, and soil nutrients such as Ca, Mg, and K (e.g., Ugolini et al., 2001; Corti et al., 2002; Cuniglio et al., 2009; Agnelli et al., 2017).

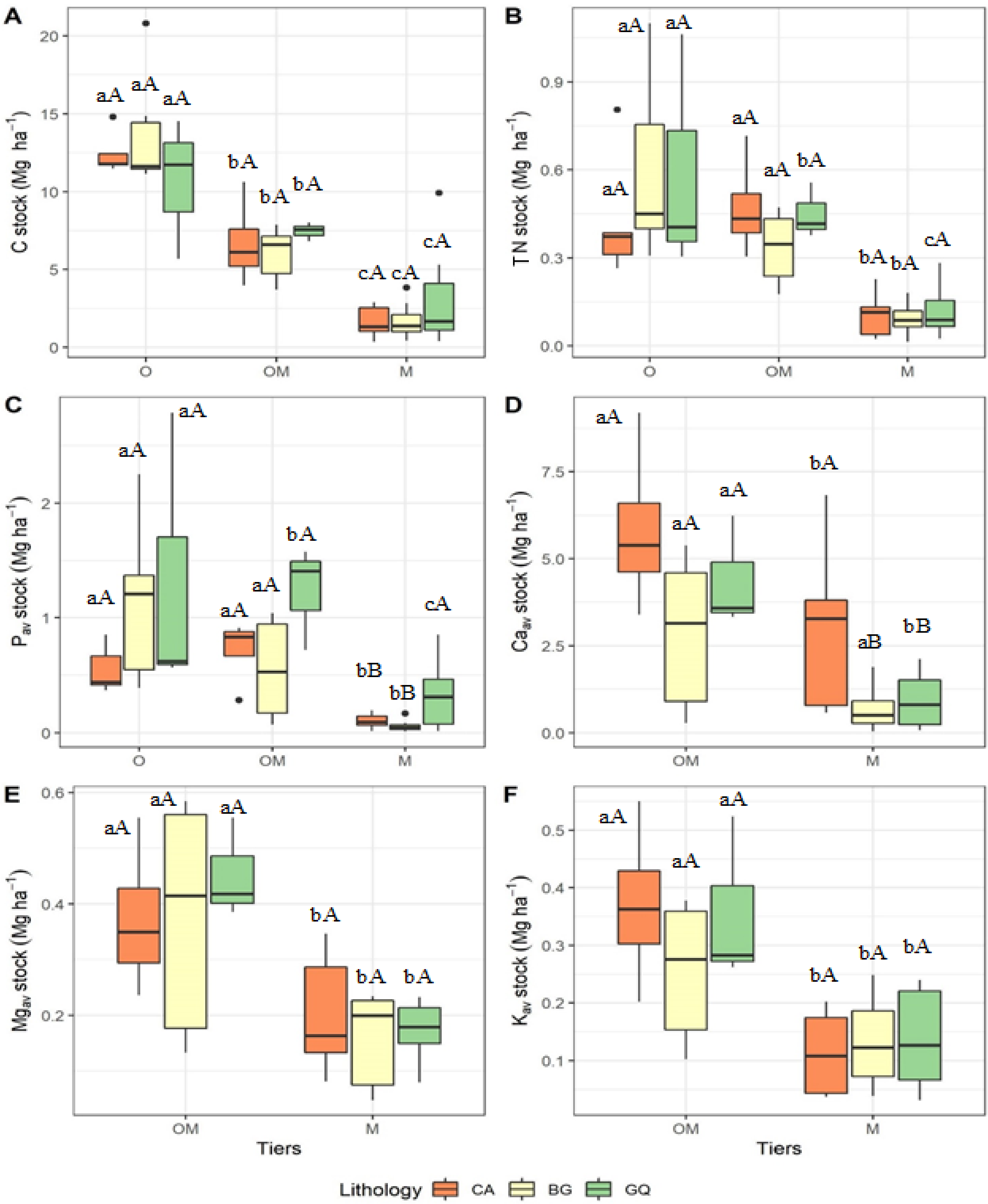


Fig. 2. Stocks of C and nutrients per 0.01 m thickness of organic (O), organo-mineral (OM), and mineral (M) tiers in the soils under Holm oak (*Quercus ilex* L.) stands over three different lithologies [calcareous (CA), granite with biotite (BG) and granite with quartzite (GQ)] in Tuscany and Sardinia, Italy. Whiskers are the standard deviations. For each property, different lowercase letters indicate differences among tiers within each soil, different capital letters indicate differences among soils for the same tier, both at $P \leq 0.05$ level of significance.

4.2. Holm oak influence on C and nutrient storage capacity

The 0.01-m stock values showed that no difference occurred among the soils, with the exceptions of P_{av} and Ca_{av} in the mineral horizons, strengthening the role of Holm oak biological activity as a factor obliterating the influence of the parent material in the accumulation of soil organic C (SOC) and nutrients. In general, the upper horizons (O and OM tiers) stored greater amounts of SOC and nutrients, and this ability decreased with depth. The stocks of organic C and TN in the organic and organo-mineral horizons were due to the large amount of organic matter in the upper part of the *solum*, and P_{av} and other nutrients to a biocycling-driven redistribution through the processes of rock weathering, uptake of nutrients by plants and their return to the soil through litter, rhizodeposition, and dead roots, and their release from organic structures via SOM mineralization (e.g., Bonifacio et al., 2015; Pistocchi et al., 2018; Ni et al., 2021). According to Bonifacio et al. (2013), in less fertile soils like those developed on BG and GQ, the release of nutrients from organic layers through SOM decomposition and their availability in the upper horizons are key factors in supporting plant nutrition.

At depth, where SOM is more stabilized by mineral colloids (e.g., Wattel-Koekkoek et al., 2003) and has a lower turnover rate than in the upper horizons (e.g., Ono et al., 2013; Yao et al., 2019), the characteristics of the parent materials become more relevant for the availability of mineral nutrients. The 0.01-m stock of Ca_{av} in the mineral tiers of CA soils was higher than that of the other soils and was ascribed to the nature of the parent material, since granitic rocks have a lower Ca_{av} content compared to limestone (Kübler et al., 2021). The lack of differences in the 0.01-m stocks for Mg_{av} and K_{av} in both OM and M tiers of all sites was attributed to a redistribution throughout the profiles due to an intense biocycling favored by Holm oak activity and a comparable content of these elements in the soils of the three sites. In fact, free Mg and K likely came from mainly the weathering of feldspars, micas, and olivines in BG and GQ soils, and from the alteration of primary and secondary minerals occurring after calcite dissolution in CA soils (Manning, 2010; Erlund et al., 2016).

5. Conclusions

Physicochemical parameters in the soil profile and the stocks of organic C and nutrients under long-time coppice-managed Holm oak forests were influenced only to a limited extent by the nature of parent materials. This was attributed to the long-time use of the forest soils in the study areas, during which plants have modified the soil properties promoting acidification, mineral weathering, SOM addition, and biocyling of nutrients along the profiles. These have weakened the influence of the parent materials on the soil properties, and resulted in them being similar in soils derived from different lithologies, especially the upper horizons. However, notwithstanding the action of living organisms and time as soil-forming forces, some distinctions did occur because of the lithology, as in the case of the influence of the calcareous parent material on the amount of Ca_{av} in the mineral horizons and in both fine earth and skeletal fractions.

This study further showed that organo-mineral and mineral horizons represent large sinks of SOC and nutrients. Therefore, since SOC stored in these horizons is slower-cycling than that of the litter, to effectively contribute to mitigating climatic change it is desirable to maintain and possibly increase the bio-ecological efficiency of forest cover and adopt forest management strategies able to increase SOM with depth rather than in the superficial organic horizons.

Acknowledgments

We are indebted to Leonardo Tonveronachi for his help with the field activities.

Funding: This work was supported by European project FutureForCoppices LIFE14 ENV/IT/000514.

References

Adamczyk, B., Sietiö, O.M., Straková, P., Prommer, J., Wild, B., Hagner, M., Pihlatie, M., Fritze, H., Richter, A., Heinonsalo, J., 2019. Plant roots increase both decomposition and stable organic matter formation in boreal forest soil. Nat. Commun. 10. https://doi.org/10.1038/s41467-019-11993-1

Agnelli, A., Celi, L., Degl'Innocenti, A., Corti, G., Ugolini F.C., 2002. The changes with depth of humic and fulvic acids extracted from fine earth and rock fragments of a forest soil. Soil Sci. 167, 524–538. https://doi.org/10.1097/00010694-200208000-00004

Agnelli, A., Cocco, S., Massaccesi, L., Courchesne, F., Ugolini, F.C., Corti, G., 2017. Features of skeleton water-extractable fines from different acidic soils. Geoderma 289, 82–96. https://doi.org/10.1016/j.geoderma.2016.11.026

Agnelli, A., Massaccesi, L., De Feudis, M., Cocco, S., Courchesne, F., Corti, G., 2016. Holm oak (*Quercus ilex* L.) rhizosphere affects limestone-derived soil under a multi-centennial forest. Plant Soil. 400, 297–314. https://doi.org/10.1007/s11104-015-2732-x

Alarcón-Gutiérrez, E., Couchaud, B., Augur, C., Calvert, V., Criquet, S., 2008. Effects of nitrogen availability on microbial activities, densities and functional diversities involved in the degradation of a Mediterranean evergreen oak litter (*Quercus ilex* L.). Soil Biol. Biochem. 40, 7, 1654-1661. https://doi.org/10.1016/j.soilbio.2008.01.020.

Arenberg, M.R., Arai, Y., 2019. Uncertainties in soil physicochemical factors controlling phosphorus mineralization and immobilization processes. Adv. Agron. 154, 153–200. https://doi.org/10.1016/BS.AGRON.2018.11.005

Baize, D., Girard, M.C., 2008. Référentiel Pedologique, Edition Quæ. Association francaise pour l'etude du sol (Afes), Versailles, France.

Bonifacio, E., Falsone, G., Catoni, M., 2013. Influence of serpentine abundance on the vertical distribution of available elements in soils. Plant Soil 368, 493-506. https://doi.org/10.1007/s11104-012-1530-y

Bonifacio, E., Petrillo, M., Petrella, F., Tambone, F., Celi, L., 2015. Alien red oak affects soil organic matter cycling and nutrient availability in low-fertility well-developed soils. Plant Soil 395, 215-229. https://doi.org/10.1007/s11104-015-2555-9

Brock, O., Kooijman, A., G.J. Nierop, K.G.J., Muys, B., Vancampenhout, K., Jansen, B., 2019. Disentangling the effects of parent material and litter input chemistry on molecular soil organic matter composition in converted forests in Western Europe. Org Geochem. 134, 66-76. https://doi.org/10.1016/j.orggeochem.2019.05.006.

Brödlin, D., Kaiser, K., Hagedorn, F., 2019. Divergent patterns of carbon, nitrogen, and phosphorus mobilization in forest soils. Front For. Global Change 2, 66. https://doi.org/10.3389/ffgc.2019.00066

Bünemann, E. K., Augstburger, S., Frossard, E., 2016. Dominance of either physicochemical or biological phosphorus cycling processes in temperate forest soils of contrasting phosphate availability. Soil Biol. Biochem. 101, 85–95. https://doi.org/10.1016/j.soilbio.2016.07.005

Calabrese, S., Richter, D.D., Porporato, A.M., 2018. The formation of clay-enriched horizons by lessivage. Geophy. Res. Lett. 45, 7588– 7595. https://doi.org/10.1029/2018GL078778

Camponi, L., Cardelli, V., Cocco, S., Serrani, D., Salvucci, A., Cutini, A., Agnelli, A., Fabbio, G., Bertini, G., Roggero, P.P., Corti, G., 2022. Effect of coppice conversion into high forest on soil organic C and nutrients stock in a Turkey oak (*Quercus cerris* L.) forest in Italy. J. Environ. Manage. 312. https://doi.org/10.1016/j.jenvman.2022.114935.

Cardelli, V., Cocco, S., Agnelli, A., Nardi, S., Pizzeghello, D., Fernández-Sanjurjo, M.J., Corti, G., 2017. Chemical and biochemical properties of soils developed from different lithologies in Northwestern Spain (Galicia). Forests 8. https://doi.org/10.3390/f8040135

Cardelli, V., De Feudis, M., Fornasier, F., Massaccesi, L., Cocco, S., Agnelli, A., Weindorf, D.C., Corti, G., 2019. Changes of topsoil under Fagus sylvatica along a small latitudinal-altitudinal gradient. Geoderma 344, 164–178. https://doi.org/10.1016/J.GEODERMA.2019.01.043

Carrari, E., Ampoorter, E., Bottalico, F., Chirici, G., Coppi, A., Travaglini, D., Verheyen, K., Selvi, F., 2017. The old charcoal kiln sites in Central Italian forest landscapes. Quat. Int. 458, 214–223. https://doi.org/10.1016/j.quaint.2016.10.027

CFS (Corpo Forestale dello Stato), CRA-MPF (Consiglio per la Ricerca in Agricoltura – Unità di ricerca per il Monitoraggio e la Pianificazione Forestale), 2005 – INFC (Inventario Nazionale delle Foreste e dei Serbatoi Forestali di Carbonio) - Secondo Inventario Forestale Nazionale.

Cheng, X., Han, H., Zhu, J., Peng, X., Li, B., Liu, H., Epstein, H.E., 2021. Forest thinning and organic matter manipulation drives changes in soil respiration in a *Larix principis-rupprechtii* plantation in China. Soil Tillage Res. 211, 104996. https://doi.org/10.1016/j.still.2021.104996

Cocco, S., Agnelli, A., Gobran, G.R., Corti, G., 2013. Changes induced by the roots of *Erica arborea* L. to create a suitable environment in a soil developed from alkaline and fine-textured marine sediments. Plant Soil 368, 297–313. https://doi.org/10.1007/s11104-012-1501-3

Corti, G., Agnelli, A., Cocco, S., Cardelli, V., Masse, J., Courchesne, F., 2019. Soil affects throughfall and stemflow under Turkey oak (*Quercus cerris* L.). Geoderma 333, 43–56. https://doi.org/10.1016/J.GEODERMA.2018.07.010

Corti, G., Agnelli, A., Ugolini, F.C., 1997. Release of Al by hydroxy-interlayered vermiculite & hydroxy-interlayered smectite during determination of cation exchange capacity in fine earth and rock fragments fractions. Eur. J. Soil Sci. 48, 249–262. 10.1111/j.1365-2389.1997.tb00545.x

Corti, G., Ugolini, F.C., Agnelli, A., Certini, G., Cuniglio, R., Berna, F., Fernández Sanjurjo, M.J., 2002. The soil skeleton, a forgotten pool of carbon and nitrogen in soil. Eur. J. Soil Sci. 53, 283–298. https://doi.org/10.1046/j.1365-2389.2002.00442.x

Cuniglio, R., Corti, G., Agnelli, A., 2009. Rock fragments evolution and nutrients release in vineyard soils developed on a thinly layered limestone (Tuscany, Italy). Geoderma 148, 375–383. https://doi.org/10.1016/J.GEODERMA.2008.11.005

Cutini, A., Ferretti, M., Bertini, G., Brunialti, G., Bagella, S., Chianucci, F., Fabbio, G., Fratini, R., Riccioli, F., Caddeo, C., Calderisi, M., Ciucchi, B., Corradini, S., Cristofolini, F., Cristofori, A., Di Salvatore, U., Ferrara, C., Frati, L., Landi, S., Marchino, L., Patteri, G., Piovosi, M., Roggero, P.P., Seddaiu, G., Gottardini, E., 2021. Testing an expanded set of sustainable forest management indicators in Mediterranean coppice area. Ecol. Indic. 130, 108040. https://doi.org/10.1016/j.ecolind.2021.108040.

De Feudis, M., Cardelli, V., Massaccesi, L., Trumbore, S.E., Vittori Antisari, L., Cocco, S., Corti, G., Agnelli, A., 2019. Small altitudinal change and rhizosphere affect the SOM light fractions but not the heavy fraction in European beech forest soil. Catena 181, 104091. https://doi.org/10.1016/j.catena.2019.104091

De Feudis, M., Falsone, G., Vianello, G., Agnelli, A., Vittori Antisari, L., 2022. Soil organic carbon stock assessment in forest ecosystems through pedogenic horizons and fixed depth layers sampling: what's the best one? Land Degrad. Develop. 33, 1446–1458. https://doi.org/10.1002/ldr.4253

De Nicola, C., Zanella, A., Testi, A., Fanelli, G., Pignatti, S., 2014. Humus forms in a Mediterranean area (Castelporziano Reserve, Rome, Italy): classification, functioning and organic carbon storage. Geoderma 235–236, 90-99. https://doi.org/10.1016/j.geoderma.2014.06.033.

Egli, M., Sartori, G., Mirabella, A., Favilli, F., Giaccai, D., Delbos, E., 2009. Effect of north and south exposure on organic matter in high Alpine soils. Geoderma 149, 124–136. https://doi.org/10.1016/J.GEODERMA.2008.11.027

Erlund, R., Koivisto, E., Fagerholm, M., Zevenhoven, R., 2016. Extraction of magnesium from four Finnish magnesium silicate rocks for CO_2 mineralisation—part 2: Aqueous solution extraction. Hydrometallurgy 166, 229–236. https://doi.org/https://doi.org/10.1016/j.hydromet.2016.07.004

Fantini, S., Fois, M., Casula, P., Fenu, G., Calvia, G., Bacchetta, G., 2020. Structural heterogeneity and old-growthness: A first regional-scale assessment of Sardinian forests. Ann. For. Res. 63, 103–120. https://doi.org/10.15287/afr.2020.1968

FAO (Food and Agriculture Organization of the United Nations), 2018. State of Mediterranean Forests 2019 – Executive Summary. http://www.fao.org/3/CA2081EN/ca2081en.PDF?fbclid=IwAR2XiKuQHU5SWkDCxb6-ALrhsmqFNb0CsQhyhcqi09TWckQKukRdBK5TOgw

Gee, G.W., Or, D., 2002. Particle-Size Analysis. In Methods of Soil Analysis (eds J.H. Dane and G. Clarke Topp). https://doi.org/10.2136/sssabookser5.4.c12

Gimeno, T.E., Pías, B., Lemos-Filhos, J.P., Valladares, F., 2009. Plasticity and stress tolerance override local adaptation in the response of Mediterranean Holm oak seedlings to drought and cold. Tree Physiol. 29, 87–98. https://doi.org/10.1093/treephys/tpn007

González, I.G., Grau Corbí, J.M., Fernández Cancio, A., Jiménez Ballesta, R., González Cascón, M.R., 2012. Soil carbon stocks and soil solution chemistry in *Quercus ilex* stands in Mainland Spain. Eur. J. For. Res. 131, 1653–1667. https://doi.org/10.1007/s10342-012-0623-8

He, X., Chi, Q., Cai, Z., Cheng, Y., Zhang, J., Müller, C., 2020. 15N tracing studies including plant N uptake processes provide new insights on gross N transformations in soil-plant systems. Soil Biol. Biochem. 141, 107666. https://doi.org/10.1016/J.SOILBIO.2019.107666

Innangi, M., Danise, T., d'Alessandro, F., Curcio, E., Fioretto, A., 2017. Dynamics of organic matter in leaf litter and topsoil within an Italian alder (*Alnus cordata* (Loisel.) Desf.) ecosystem. Forests 8. https://doi.org/10.3390/f8070240

Johnson, D.W., Turner, J., 2019. Nutrient cycling in forests: A historical look and newer developments. Forest Ecol. Manag. 444, 344-373. https://doi.org/10.1016/j.foreco.2019.04.052.

Kirkby, C.A., Richardson, A.E., Wade, L.J., Batten, G.D., Blanchard, C., Kirkegaard, J.A., 2013. Carbon-nutrient stoichiometry to increase soil carbon sequestration. Soil Biol. Biochem. 60, 77–86. https://doi.org/10.1016/j.soilbio.2013.01.011

Kübler S., Rucina S., Aßbichler D., Eckmeier E., King G., 2021. Lithological and Topographic Impact on Soil Nutrient Distributions in Tectonic Landscapes: Implications for Pleistocene Human-Landscape Interactions in the Southern Kenya Rift. Front. Earth Sci. 9. https://doi.org/10.3389/feart.2021.611687

Manning, D.A.C., 2010. Mineral sources of potassium for plant nutrition. A review. Agron. Sustain. Dev. 30, 281–294. https://doi.org/10.1051/agro/2009023

Marco, A. De, Fioretto, A., Giordano, M., Innangi, M., Menta, C., Papa, S., De Santo, A.V., 2016. C stocks in forest floor and mineral soil of two Mediterranean beech forests. Forests 7, 1–20. https://doi.org/10.3390/f7080181

Nelson, D.W., Sommers, L.E., 1996. Total Carbon, Organic Carbon, and Organic Matter, in Sparks, D., Page, A., Helmke, P., Loeppert, R.H., Soltanpour, P.N. Tabatabai, M.A., Johnston, C.T., Sumner, M.E. (Eds.), Methods of Soil Analysis. SSSA Book Series. https://doi.org/10.2136/sssabookser5.3.c34

Neumann, G., Römheld, V., 2012. Rhizosphere Chemistry in Relation to Plant Nutrition, in: Marschner, P. (Ed.), Marschner's Mineral Nutrition of Higher Plants (Third Edition). Academic Press, San Diego. Chapter 14, pp. 347–368. https://doi.org/https://doi.org/10.1016/B978-0-12-384905-2.00014-5

Ni, X., Lin, C., Chen, G., Xie, J., Yang, Z., Liu, X., Xiong, D., Xu, C., Yue, K., Wu, F., Yang, Y., 2021. Decline in nutrient inputs from litterfall following forest plantation in subtropical China. Forest Ecol. and Manag. 496, 119445. https://doi.org/10.1016/j.foreco.2021.119445.

Olsen, S.R., Cole, C.V., Watanabe, F.S. and Dean, L.A. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate, USDA. Circular 939

Ono, K., Hiradate, S., Morita S., Hirai, K., 2013. Fate of organic carbon during decomposition of different litter types in Japan. Biogeochem. 112, 7-12. https://doi.org/10.1007/s10533-011-9682-z

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. Science 333, 988-993. https://doi.org/10.1126/science.1201609

Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Köppen-Geiger climate classification. Hydrol. Earth Syst. Sci. 11, 1633–1644. https://doi.org/10.5194/hess-11-1633-2007

Penn, C.J., Camberato, J.J., 2019. A Critical Review on Soil Chemical Processes that Control How Soil pH Affects Phosphorus Availability to Plants. Agriculture 9, 120. https://doi.org/10.3390/agriculture9060120

Pistocchi, C., Mészáros, É., Tamburini, F., Frossard, E., Bünemann, E.K., 2018. Biological processes dominate phosphorus dynamics under low phosphorus availability in organic horizons of temperate forest soils. Soil Biol. Biochem. 126, 64–75. https://doi.org/10.1016/j.soilbio.2018.08.013

Pulido, F.J., Díaz, M., Hidalgo De Trucios, S.J., 2001. Size structure and regeneration of Spanish holm oak *Quercus ilex* forests and dehesas: Effects of agroforestry use on their long-term sustainability. For. Ecol. Manage. 146, 1–13. https://doi.org/10.1016/S0378-1127(00)00443-6

Quénard, L., Samouëlian, A., Laroche, B., Cornu, S., 2011. Lessivage as a major process of soil formation: A revisitation of existing data. Geoderma 167–168, 135-147. https://doi.org/10.1016/j.geoderma.2011.07.031.

Scharenbroch, B.C., Bockheim, J.G., 2007. Impacts of forest gaps on soil properties and processes in old growth northern hardwood-hemlock forests. Plant Soil. 294, 219-233. https://doi.org/10.1007/s11104-007-9248-y

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Soil Survay Staff, 2012. Field Book for Describing and Sampling Soils, Version 3.0. https://doi.org/10.1038/258254a0

Skorupa, A.L.A., Silva, S.H.G., Poggere, G.C., Tassinari, D., Pinto, L.C., Zinn, Curi, Y. L. N., 2017. Similar Soils but Different Soil-Forming Factors: Converging Evolution of Inceptisols in Brazil. Pedosphere 27- 4, 747-757. https://doi.org/10.1016/S1002-0160(17)60443-0.

Sorenson, P.T., Quideau, S.A., MacKenzie, M.D., Landhäusser, S.M., Oh, S.W., 2011. Forest floor development and biochemical properties in reconstructed boreal forest soils. Appl. Soil Ecol. 49, 139–147. https://doi.org/10.1016/J.APSOIL.2011.06.006

Ugolini, F.C., Corti, G., Agnelli, A., Piccardi, F., 1996. Mineralogical, physical, and chemical properties of rock fragments in soil. Soil Sci. 161, 521-542. https://doi.org/10.1097/00010694-

199608000-00007

Ugolini, F.C., Corti, G., Dufey, J.E., Agnelli, A., Certini, G., 2001. Exchangeable Ca, Mg, and K of rock fragments and fine earth from sandstone and siltstone derived soils and their availability to grass. J. Plant Nutr. Soil Sci. 164, 309-315. https://doi.org/10.1002/1522-2624(200106)164:3<309::AID-JPLN309>3.0.CO;2-8

Unrau, A., Becker, G., Spinelli, R., Lazdina, D., Magagnotti, N., Nicolescu, V.-N., Buckley, P., Bartlett, D., Kofman, P.D., (Eds.)., 2018. Coppice Forests in Europe. EuroCoppice COST Action, Albert Ludwig University of Freiburg, Germany. Retrieved from https://www.eurocoppice.unifreiburg.de/coppice-forests-in-europe

Vacca, A., Serra, G., Scalenghe, R., 2018. Vegetation, soils, and humus forms of Sardinian holm oak forests and approximated cross-harmonization of vegetation types, WRB Soil Groups and humus forms in selected Mediterranean ecosystems. Appl. Soil Ecol. 123, 659-663. https://doi.org/10.1016/j.apsoil.2017.06.024.

Vindušková, O., Pánek, T., Frouz, J., 2019. Soil C, N and P dynamics along a 13 ka chronosequence of landslides under semi-natural temperate forest. Quat. Sci. Rev. 213, 18–29. https://doi.org/10.1016/J.QUASCIREV.2019.04.001

Wattel-Koekkoek, E.J.W., Buurman, P., van der Plicht, J., Wattel, E., van Breemen, N., 2003. Mean residence time of soil organic matter associated with kaolinite and smectite. Eur. J. Soil Sci. 54, 1-10. https://doi.org/10.1046/j.1365-2389.2003.00512.x

Wilson, S.G., Dahlgren, R.A., Margenot, A.J., Rasmussen, C., O'Geen, A.T., 2022. Expanding the Paradigm: The influence of climate and lithology on soil phosphorus. Geoderma 421, 115809. https://doi.org/10.1016/j.geoderma.2022.115809.

Yao, S., Zhang, Y.L., Han, Y., Han, X.Z., Mao, J.D., Zhang, B., 2019. Labile and recalcitrant components of organic matter of a Mollisol changed with land use and plant litter management: An advanced 13C NMR study. Sci. of The Total Environ. 660, 1-10. https://doi.org/10.1016/j.scitotenv.2018.12.403

Zheng, S., Xia, Y., Hu, Y., Chen, X., Rui, Y., Gunina, A., He, X., Ge, T., Wu, J., Su, Y., Kuzyakov, Y., 2021. Stoichiometry of carbon, nitrogen and phosphorus in soil: effects of agricultural land use and climate at a continental scale. Soil Tillage Res. 209-104903. https://doi.org/10.1016/j.still.2020.104903

Appendix – Supplementary data

Table S1 - General features of the study sites and morphology of one of the three profiles opened at each site under Holm oak (*Quercus ilex* L.) stands in Tuscany and Sardinia, Italy. For symbols see legend.

Horizon[a]	Depth	Thickness	Colour[b]	Structure[c]	Consistence[d]	Roots[e]	Boundary[f]	Skeleton[g]	Other observations
	cm							%	
ALBERESE (Leccetella) (42.647759 N, 11.093969 E). Steep slope (15%); Exposure: N-NW; Mean altitude: 212 m; Mean annual air temperature: 13.9°C; Mean annual precipitation: 638 mm.									
General information. Extension of the study area: ≈1000 m^2. Holm oak stored coppice in conversion to high forest. At the time of survey, one thinning had been done. Trees per ha: 708. Basal area per ha: 23 m^2. Mean dbh: 20.3 cm. Mean height: 13.7 m. Age of standing crop 74 years. The soil surface showed signs of a diffuse boar activity. Intense soil erosion mainly due to stemflow. About 30% of the area is occupied by a small compluvium with accelerated erosion that caused enrichment of rock fragments at surface (≈60%). In the area there are two charcoal kilns with a fan shape, with maximum dimensions of 12x8 m. Outcropping rock: 0%. Soil cover [according to the "percent of area covered" tables reported in Schoeneberger et al. (2012)]: ≈75% [15% due to litter; 60% due to rock fragments (cobbles and stones)]; 25% uncovered with missing organic layers. Vegetation. Trees: *Quercus ilex* L. (95%), *Fraxinus ornus* L. (5%). Understorey: absent, except for mosses as soil coverage. Where litter is present, it is massively mixed by boar activity.									
Soil. Parent material: massive limestone with veins of calcite and flintstone. Average thickness of the *solum* (A+B horizons): 76 cm (extremes: 25-51 cm). Drainage class: well-drained. All the area is fruit of old landslide. Soil: Typic Humixerept (Soil Survey Staff, 2014). Morphology of soil replicate 2 follows.									
OLn	4-2	2-3	-	-	-	0	cw	60	Undecomposed leaves and little branches of *Q. ilex*
OLv	2-0.5	2-3	-	-	-	0	cw	60	Undecomposed leaves and little branches of *Q. ilex*
OH	0.5-0	0-0.5	5YR 3/2	-	-	0	ab	60	-
A	0-5	3-6	5YR 3/1	3f-m sbk	fr	2mi,vf,f,m	aw	60	-
Bw1	5-14	9-10	7.5YR 4/4	3m sbk	fi	1mi,vf,f;	sw	50	-

						2m,co			
Bw2	14-32	17-21	7.5YR 4/6	3c sbk	fi	1mi,vf,f,m; 3co	cw	30	-
Bw3	32-40	16-18	7.5YR 5/8	3f abk	fi	1mi,vf,f,m; 3co	sw	10	Mycelium +. Rock fragments are altered
Bwb	40-50	8-10	10YR 5/6	3m abk-sbk	fr-fi	1f,m; 3co	cw	60	-
Cb	50-65+	-	10YR 5/6	2m abk	fr	1f,m; 2co	-	70	limestone

POGGIO AI LECCI (42.642564 N, 11.092539 E). Steep slope (20-25%); Exposure: N; Mean altitude: 387 m; Mean annual air temperature: 13.3°C; Mean annual precipitation: 658 mm.

General information. Extension of the study area: ≈600 m^2. Holm oak stored coppice in conversion to high forest. No thinning over in the last 30 years. Trees per ha: 2967. Basal area per ha: 33.6 m^2. Mean dbh: 12 cm. Mean height: 10.7 m. Age of standing crop: 74 years.

The soil surface showed signs of a great diffuse boar activity. Intense laminar erosion partly due to stemflow; ≈10% of the area is interested by rills departing from the base of Holm oak stems.

Outcropping rock: 10%. Soil cover [according to the "percent of area covered" tables reported in Schoeneberger et al. (2012)]: ≈55% [5% due to litter; 50% due to rock fragments (cobbles and stones)].

Vegetation. Trees: *Quercus ilex* L. (70%), *Arbutus unedo* L. (15%), *Fraxinus ornus* L. (10%), *Pistacia lentiscus* L. (5%). Understorey: *Cyclamen repandum* Sibth. & Sm. Where litter is present, it is massively mixed by boar activity.

Soil. Parent material: calcareous sandstone interbedded with yellowish schistose marls with small presence of anagenite and limestone. Average thickness of the *solum* (A+B horizons): 35 cm (extremes: 31-38 cm). Drainage class: well-drained. All the area is covered by old landslide. Soil: Typic Humixerept (Soil Survey Staff, 2014). Morphology of soil replicate 1 follows.

OL	3-0	1-3	-	-	-	0		50	Undecomposed leaves and little branches of *Q. ilex*
A	0-1	1-2	5YR 3/2	2-3f gr	fr	2mi,vf,f,m	cw	50	-
AB	1-3	2-3	5YR 3/4	1-3f,m gr+sbk	fr-fi	3mi,vf,f,m,co	cw	50	-

BA	3-8	2-6	5YR 4/6	3m,co abk-sbk	fr-fi	2mi,vf,f; 3mco	cw	35	Mycelium +
Bw	8-31	20-25	5YR 4/6	3f,m abk	fr-fi	1mi,vf,f; 2mco	cw	40	nuciform structure
C&Bb	31-35+	-	5YR 5/3	2f,m abk	fr	1mi,vf,f,m; 3co	-	60	-

ALBATRAIA (42.650182 N, 11.095987 E). Steep slope (15-20%); Exposure: W; Mean altitude: 133 m; Mean annual air temperature: 14.3°C; Mean annual precipitation: 630 mm.

General information. Extension of the study area: ≈700 m^2. Holm oak stored coppice in conversion to high forest. Forest was under natural evolution until 2010, when the first thinning occurred. Trees per ha: 1740. Basal area per ha: 38 m^2. Mean dbh: 16.8 cm. Mean height: 15.6 m. Age of standing crop: 74 years.

The soil surface showed signs of a diffuse boar activity. Intense laminar erosion partly due to stemflow; ≈10% of the area is interested by rills departing from the base of Holm oak stems. About 30% of the area is occupied by a primary gulch, while ≈20% of the area is occupied by a secondary tributary gulch. A small charcoal kiln is present (6x8 m). The remaining 50% of the area is occupied by 10% of outcropping rock and rock blocks of large dimensions.

Outcropping rock: 10%. Soil cover [according to the "percent of area covered" tables reported in Schoeneberger et al. (2012)]: ≈55% [15% due to litter; 40% due to rock fragments (cobbles)]; half of the surface shows signs of boar activity. Uncovered soil: 45%, in the vicinity of the gulches.

Vegetation. Trees: *Quercus ilex* L. (90%), *Fraxinus ornus* L. (10%). Understorey: absent.

Soil. Parent material: limestone with flintstone veins and small presence of anagenite. Average thickness of the *solum* (A+B horizons): 51 cm (extremes: 41-58 cm). Drainage class: well-drained. Soil: Typic Humixerept (Soil Survey Staff, 2014). Morphology of soil replicate 2 follows.

OL/OH	2-0	2-4	-	-	-	0	cb	40	Undecomposed leaves and little branches of *Q. ilex*, *F. ornus*, *Q. cerris*, *Cornus* spp.
A	0-3	1-3	7.5YR 3/1	3f gr	fr	1mi,vf; v1 f	cw	40	
AB	3-4	3-4	7.5YR 4/2	2f gr	fr	2mi,vf,f	cw	50	Mycelium +
Bw1	4-9	3-6	10YR 6/4 10YR 5/2	3m,co abk	fi	3mi,vf,f,m	cw	50	Roots in cracks

Bw2	9-26	12-20	10YR 7/4 10YR 6/4	3m,co abk	fr-fi	3mi,vf,f,m; 1co	cw	60	More cracks; 50% of the horizon interested by crack web
Bw3	26-46	16-22	10YR 7/4	3f,m,co abk-sbk	fr-fi	3mi,vf,f,m,co	cw	60	-
BC	46-50+	-	10YR 7/3	1m abk	fr	2mi,vf,f,m,co	-	60	-

IS CANNONERIS 1 (39.050949 N, 8.841186 E). Steep slope (17%); Exposure: SSE; Mean altitude: 905 m; Mean annual air temperature: 12.3°C; Mean annual precipitation: 615 mm.

General information. Extension of the study area: ≈1200 m^2. Holm oak stored coppice in conversion to high forest. At the time of survey two thinnings had been done. Trees per ha: 2356. Basal area per ha: 30 m^2. Mean dbh: 15.2 cm. Mean height: 12 m. Age of standing crop: 62 years.

The soil surface showed signs of boar activity and of slight to medium erosion.

Outcropping rock: 0%. Soil cover [according to the "percent of area covered" tables reported in Schoeneberger et al. (2012)]: ≈55% [40% due to litter and branches; 15% due to rock fragments (pebbles and cobbles)]. A few dead standing trees are present.

Vegetation. Trees: *Quercus ilex* L. (100%). Understorey: *Pistacia lentiscus* L., *Erica arborea* L., *Cyclamen* sp., *Arbutus unedo* L., moss.

Soil. Parent material: biotite granite. Average thickness of the *solum* (A+B horizons): 56 cm (extremes: 25-96 cm). Drainage class: well-drained. Soil: Typic Humixerept (Soil Survey Staff, 2014). Morphology of soil replicate 3 follows.

OLn/OLv	8-5	1-5	-	-	-	0	cw	15	Undecomposed leaves, acorns, and little branches of *Q. ilex*
OLt	5-4	1-2	10YR 3/2	-	-	0	cw	15	
OH	4-0	0-2	10YR 6/3 5YR 2.5/1	v1f,m sbk-abk	vfr	1mi,vf,f	cb	10	75% Mycelium +++; mesofauna
A	0-2	0-2	10YR 2/2	3f,m,gr sbk-abk	fr	2mi,vf, f	cb	25	Mycelium ++
AB	2-8	3-9	10YR 3/6	3f,m,sbk-abk	fr	2mi,vf, f	cb	25	Mycelium ++

Bw1	8-33	2-16	7.5YR 4/4	3f,m sbk-abk	fr	2mi,vf, 3f, m, co	cw	25	Mycelium ++
Bw2	33-53	0-20	7.5YR 4/6	3f,m sbk-abk	fr	1 mi,vf, 2f,m, 1co	cb	50	Mycelium +
BC	53-66	12-16	7.5YR 5/4	1m sbk-abk	fr	1mi,vf,f 2m,co	cw	80	-
C	66-68+	-	5YR 5/3	-	fr	1mi,vf,f,m,co	-	90	Presence of openwork at sites

IS CANNONERIS 2 (39.050584 N, 8.839875 E). Steep slope (17%); Exposure: SSE; Mean altitude: 915 m; Mean annual air temperature: 12.3°C; Mean annual precipitation: 615 mm.

General information. Extension of the study area: ≈1000 m^2. Holm oak stored coppice in conversion to high forest. At the moment of survey two thinnings had been done. Trees per ha: 1935. Basal area per ha: 31.6 m^2. Mean dbh: 17.8 cm. Mean height: 12.4 m. Age of standing crop: 62 years.

The soil surface showed signs of a great boar activity and of slight erosion.

Outcropping rock: 0%. Soil cover [according to the "percent of area covered" tables reported in Schoeneberger et al. (2012)]: ≈65% [50% due to litter and branches; 15% due to rock fragments (pebbles and cobbles)]. Many dead standing trees (mostly *Arbutus unedo* L.) are present.

Vegetation. Trees: *Quercus ilex* L. (100%). Understorey: *Pistacia lentiscus* L., *Erica arborea* L., *Rubus ulmifolius* Schott, *Cyclamen* sp., *Arbutus unedo* L., moss.

Soil. Parent material: biotite granite. Average thickness of the *solum* (A+B horizons): 42 cm (extremes: 21-66 cm). Drainage class: well-drained. Soil: Typic Humixerept (Soil Survey Staff, 2014). Morphology of soil replicate 2 follows.

OLn/OLv	8-3	2-5	-	-	-	0	cw	15	Undecomposed leaves, acorns, and little branches of *Q. ilex*
OLt	3-2	1-2	7.5YR 3/2	-	-	0	cw	15	mesofauna
OH	2-0	0-2	7.5YR2.5/2	1f,cr	fr	1mi,vf,f	cb	15	
E	0-3	0-3	10YR 5/4	1-2 f,m gr-sbk	fr	2mi,vf,f	cw	10	
A	0-3	0-3	7.5YR 3/3	3f,m gr-abk	fr	1mi,vf,f	cb	20	Mesofauna, Micelyum +

AB	3-7	2-6	7.5YR 4/2	3f,m gr-abk	fr	3mi,vf,f, 1m	cw	20	Mesofauna, Micelyum +
Bw1	7-30	20-23	7.5YR 4/4	3f,m abk-sbk	fr	2mi,vf,f,m,co	cw	40	Mesofauna, Micelyum +
Bw2	30-60	30-32	7.5YR 4/6	3f,m sbk-abk	fr	1mi,vf 2f 3m,co	cw	50	Mycelium +
Cr	60-65+	-	10YR 5/6	1m abk	fr	1mi,vf,f,m,co	-	80	-

IS CANNONERIS 3 (39.049550 N, 8.838266 E). Very steep slope (35%); Exposure: E; Mean altitude: 905 m; Mean annual air temperature: 12.3°C; Mean annual precipitation: 615 mm.

General information. Extension of the study area: ≈800 m^2. Holm oak stored coppice in conversion to high forest. At the moment of survey two thinnings had been done. Trees per ha: 2371. Basal area per ha: 30.5 m^2. Mean dbh: 15 cm. Mean height: 12 m. Age of standing crop: 62 years.

The soil surface showed signs of a great boar activity and of slight erosion.

Outcropping rock: 0%. Soil cover [according to the "percent of area covered" tables reported in Schoeneberger et al. (2012)]: ≈75% [60% due to litter and branches; 15% due to rock fragments (pebbles and cobbles)]. Many dead stand trees (mostly *Arbutus unedo* L.) are present.

Vegetation. Trees: *Quercus ilex* L. (100%), Understorey: *Arbutus unedo* L., *Erica arborea* L., *Phillyrea latifolia* L., *Cistus* sp., *Smilax aspera* L., *Hedera elix* L., *Rubus ulmifolius* Schott, *Cyclamen* sp., *Lamium* sp., *Stellaria* sp., moss.

Soil. Parent material: biotite granite. Average thickness of the *solum* (A+B horizons): 63 cm (extremes: 23-126 cm). Drainage class: well-drained. Soil: Typic Humixerept (Soil Survey Staff, 2014). Morphology of soil replicate 2 follows.

OLn/OLv	6-2	3-4	-	-	-	0	cw	15	Undecomposed leaves, acorns, and little branches of *Q. ilex*. Mesofauna
OLt/OH	2-0	1-2	7.5YR 2.5/2	-	-	0	cw	15	Mesofauna
A	0-5	3-5	7.5YR 3/3	3f,m gr-sbk	fr	1mi,vf 2f,m	cw	15	Mycelium +
EB	5-12	5-9	7.5YR 4/6	3f,m sbk	fr	1mi,vf 3f,m	cw	20	Mycelium +
Bw1	12-58	44-48	10YR 5/4	3f,m abk	fr	1mi,vf 3f,m,co	cw	30	-

Bw2	58-86	25-30	7.5YR 4/6	3f,m abk	fr	1mi,vf,f 2m; 1co	cw	60	-
Bw3	86-106	16-22	10YR 4/6	3-2f-m abk	fr	1mi,vf,f,co 2m	cw	60	-
Cr	106-112+	-	10YR 4/6	2m abk	fr	1mi,vf,f,co	-	95	-

SETTE FRATELLI 1 (39.275739 N, 9.431211 E). Moderate slope (5%); Exposure: SSE; Mean altitude: 778 m; Mean annual air temperature: 12.5°C; Mean annual precipitation: 695 mm.

General information. Extension of the study area: ≈1500 m^2. Holm oak stored coppice in conversion to high forest. At the moment of survey two thinnings had been done. Trees per ha: 1716. Basal area per ha: 44.5 m^2. Mean dbh: 18.1 cm. Mean height: 14.2 m. Age of standing crop: 69 years. The oldest trees are ≈80 years old.

The soil surface showed signs of a diffuse boar activity over 1/3 of the area and of slight erosion. A charcoal kiln of 8x11 m is present in the area.

Outcropping rock: 0%. Soil cover [according to the "percent of area covered" tables reported in Schoeneberger et al. (2012)]: 100% [40% due to litter and branches; 60% due to rock fragments (cobbles and stones)]. Many dead standing trees (mostly *Arbutus unedo* L.) are present.

Vegetation. Trees: *Quercus ilex* L. (100%). Understorey: *Arbutus unedo* L., *Erica arborea* L., *Phillyrea latifolia* L., *Smilax aspera* L., *Cyclamen* sp., moss.

Soil. Parent material: granite with coarse veins of quartz and few small veins of pegmatite. Average thickness of the *solum* (A+B horizons): 55 cm (extremes: 48-63 cm). Drainage class: well-drained. Soil: Typic Humixerept (Soil Survey Staff, 2014). Morphology of soil replicate 3 follows.

OLn/OLv/A	3.5-0.5	2-8	7.5YR 2.5/1	-	-	0	cw	60	Undecomposed leaves, acorns, and little branches of *Q. ilex*; mesofauna
OLt/OH	0.5-0	1-2	7.5YR 2.5/2	-	-	0	cw	60	Few mesofauna
A	0-2	7-10	7.5YR 2.5/2	2f-m sbk	fr	1mi,vf,f	cw	60	Mycelium+
EB	2-11	26-30	10YR 4/3	2f abk-sbk	fr	1mi,vf; 2f,m	cw	40	Mycelium+
Bw1	11-38	20-22	7.5YR 3/4	2f-m abk-sbk	fr	2mi,vf,f; 3m,co	cw	40	Mycelium+
Bw2	38-58	8-10	7.5YR 3/4	2f,m	fr	v1mi,vf; 1f	cw	60	Mycelium+

				sbk+abk					
BC	58-68	7-12	7.5YR 4/6	2m sbk-abk	fr	v1mi,vf; 1f	cw	80	-
Cr	68-75+	-	7.5YR 5/4	1m abk	fr	v1mi,vf,f	-	95	-

SETTE FRATELLI 2 (39.273689 N, 9.429820 E). Moderate slope (5%); Exposure: SW; Mean altitude: 760 m; Mean annual air temperature: 12.5°C; Mean annual precipitation: 695 mm.

General information. Extension of the study area: ≈2000 m^2. Holm oak stored coppice in conversion to high forest. At the time of survey two thinnings had been done. Trees per ha: 2912. Basal area per ha: 38.8 m^2 . Mean dbh: 13 cm. Mean height: 9.7 m. Age of standing crop: 69 years.

The soil surface showed signs of a great boar activity over 40% of the area and of slight erosion.

Outcropping rock: 0%. Soil cover [according to the "percent of area covered" tables reported in Schoeneberger et al. (2012)]: 100% [40% due to litter and branches; 60% due to rock fragments (cobbles and stones)]. A few dead standing trees (mostly *Arbutus unedo* L.) are present.

Vegetation. Trees: *Quercus ilex* L. (100%). Understorey: *Arbutus unedo* L., *Erica arborea* L., *Phillyrea latifolia* L., *Cyclamen* sp., *Crataegus azarolus* L., moss.

Soil. Parent material: granite with coarse veins of quartz and few small veins of pegmatite. Average thickness of the solum (A+B horizons): 64 cm (extremes: 42-80 cm). Drainage class: well-drained. Soil: Typic Humixerept (Soil Survey Staff, 2014). Morphology of soil replicate 2 follows.

OLn/OLv/A	4-1	2-7	7.5YR 2.5/2	-	-	0	cw	60	Undecomposed leaves, acorns, and little branches of *Q. ilex*; mesofauna
OLt	1-0	0.5-2	7.5YR 2.5/2	-	-	0	cw	60	mesofauna
A	0-8	5-9	7.5YR 3/2	3f-m sbk	fr	1mi,vf; 1f	cw	60	-
EB	8-20	9-13	10YR 4/3	3f sbk-abk	fr	2mi,vf,f; 1m; 3co	cw	20	-
Bw1	20-47	25-30	7.5YR 4/3	3f,m abk	fr	2mi,vf,f; 3m,co	cw	25	-
Bw2	47-65	15-20	7.5YR 3/4	3f,m sbk	fr	1mi,vf; 2f,m,co	cw	25	-

Cr	65-80+	-	7.5YR 4/5	1m abk	fr	1mi,vf,f,m,co	-	60	-

[a] Horizons: designation according to Baize et al. (2008) for organic horizons, to Schoeneberger et al. (2012) for mineral horizons.

[b]Colour: moist and crushed, according to the Munsell Soil Color Charts.

[c]Structure: 1=weak, 2=moderate, 3=strong; f=fine, m=medium, c=coarse; gr=granular, abk=angular blocky, sbk=sub-angular blocky; fi=firm; m= moist; fr, friable; vfr, very friable; w, wet; ss, slightly sticky.

[d]Consistence: fi=firm; m= moist; fr, friable; vfr=very friable; w=wet; ss=slightly sticky.

[e]Roots: 0=absent, v_1=very few, 1=few, 2=plentiful, 3=abundant; mi=micro, vf=very fine, f=fine, m=medium, co=coarse.

[f]Boundary: a=abrupt; c=clear; g=gradual; d=diffuse; s=smooth; w=weavy; i=irregular; b=broken.

[g]Skeleton: by sight, according to the "percent of area covered" tables reported in Schoeneberger et al. (2012).

Point 1. Soil analyses. From Camponi et al. (2022)

The particle-size distribution was determined by the pipette method (Day, 1965) after that 20 g of fine earth were maintained submerged in deionised water for 24 h. Sand was obtained by wet sieving at 0.053 mm, while silt was separated from clay by sedimentation. For both fine earth and skeleton, the pH values were determined potentiometrically in water with solid:liquid ratio of 1:2.5; pH of organic samples was determined on a solid:liquid ratio of 1:8. The total organic carbon (TOC) content was estimated by K-dichromate digestion, heating the suspension at 165°C for 30 minutes (Nelson and Sommers, 1996). The total nitrogen (TN) content was measured by a dry combustion analyser (EA-1110, Carlo Erba Instruments, Milan, Italy). The potentially available P (P_{av}) was determined per Olsen et al. (1954). Potentially available nutrients (Ca_{av}, Mg_{av}, and K_{av}) were displaced by a 0.2 M $BaCl_2$ solution (solid:liquid ratio 1:10) (Corti et al., 1997). After filtration, elements were determined by atomic absorption with a Shimadzu AA-6300 spectrophotometer (Tokyo, Japan). For the skeletal fraction, TOC and TN were measured on ground aliquots, while pH, P_{av}, Ca_{av}, Mg_{av}, and K_{av} were determined on unground rock fragments.

For the mineral samples, the bulk density of fine earth and skeleton was calculated from the weight of the samples hated at 105° C. Previously, the total volume of the cylinder had been subtracted of the volume of the skeleton determined by water displacement of the water-saturated rock fragments (Corti et al., 1998), obtaining the volume of the fine earth.

The bulk density of the organic horizons was calculated starting from the percentage of organic C once the content of organic matter (OM) was estimated (OM = 2 • organic C), through the pedotransfer functions of De Nicola et al. (2014), which has been adopted by several authors on different soil types (Brenna et al., 2010; Garlato et al., 2009a,b; Guermandi et al., 2013). The equations are:

1. For OM > 30%: bulk density (g cm^{-3}) = 0.00589 • organic C + 0.554;
2. For OM = 30–15%: bulk density (g cm^{-3}) = 0.00745 • organic C + 0.593;
3. For OM < 15%: bulk density (g cm^{-3}) = 0.00797 • organic C + 0.553.

Point 2. Procedure to obtain a proper estimation of the C and nutrients stocks in the litter and in two soil mineral depths intervals (0-0.3 and 0.3-0.5 m). From Camponi et al. (2022)

The estimations of C, TN, P_{av}, Ca_{av}, Mg_{av}, and K_{av} stocks were made for each genetic horizon taking into consideration both fine earth and skeleton according to the formula:

$$ES = EC \bullet BD \bullet TH \bullet CC \quad (1)$$

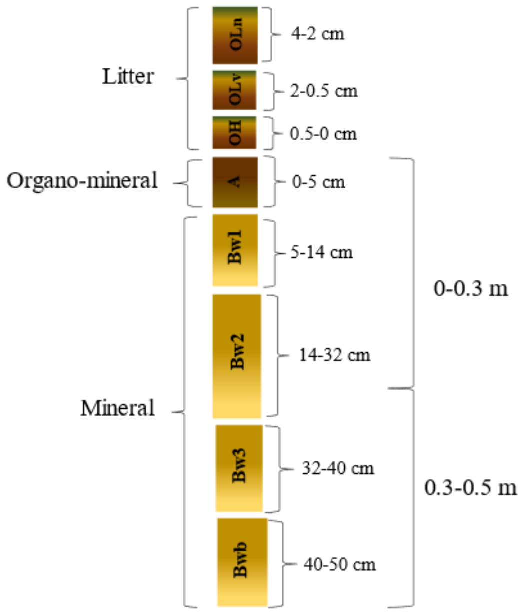
where ES = amount of element stocked in the fine earth or in the skeleton considering each fraction as the only component of the genetic horizon, expressed as Mg ha^{-1} for C and TN, and in kg ha^{-1} for P_{av}, Ca_{av}, Mg_{av}, and K_{av}; EC = element concentration in the fine earth or in the skeleton, expressed as g kg^{-1} for C and N, and in mg kg^{-1} for P_{av}, Ca_{av}, Mg_{av}, and K_{av}; BD = bulk density of fine earth or skeleton, expressed as kg dm^{-3}; TH = horizon thickness, in cm; CC = coefficient applied to normalize the units of measure (10^{-1} for C, TN, and P_{av}; 10^{-4} for Ca_{av}, Mg_{av}, and K_{av}).

Thus, the total contents of C and nutrients stored in each genetic horizon were determined as the weighed mean for the fine earth and skeleton contents:

$$ES_{TOT} = [(ES_{fe} \bullet FE\%) + (ES_{sk} \bullet SK\%)] / 100 \quad (2)$$

where ES_{TOT} = total amount of element stored in the genetic horizon, expressed as Mg ha^{-1} for C and TN, and in kg ha^{-1} for P_{av}, Ca_{av}, Mg_{av}, and K_{av}; ES_{fe} = amount of element contained in the fine earth, expressed as Mg ha^{-1} for C and TN, and in kg ha^{-1} for P_{av}, Ca_{av}, Mg_{av}, and K_{av}; FE% = percentage of fine earth content in the horizon; ES_{sk} = amount of element contained in the skeleton, expressed as Mg ha^{-1} for C and TN, and in kg ha^{-1} for P_{av}, Ca_{av}, Mg_{av}, and K_{av}; SK% = percentage of skeleton content in the horizon.

The stocks per depth intervals (litter, 0-0.3 m, and 0.3-0.5 m) is the result of the sum of each horizon contribution until the fixed depth as shown in the example below (not in scale):



For each element, the amount stored by 0.01-m thickness of the organic, organo-mineral, and mineral tiers was calculated according to the formula:

$$ES_{tier} = \frac{\left(ES_{TOT1} + ES_{TOT2} + \ldots + ES_{TOTn}\right)}{Th_{tier}} \quad (3)$$

where ES_{tier} = amount of element stored by 0.01 m thickness of each tier, ES_{TOT} = total amount of element stored in each genetic horizon, Th_{tier}= tier thickness, n= horizons number

Table S2. Bulk density and contents of C and nutrients of fine earth in the soils under Holm oak (*Quercus ilex* L.) stands developed on different parent materials (calcareous, biotite granite, and granite with quartzite veins). Tuscany and Sardinia, Italy.

Parent material	Profile	Horizon	Bulk density	TOC	TN	P_{av}	Ca_{av}	Mg_{av}	K_{av}
			g cm^{-3}	g kg^{-1}		mg kg^{-1}			
Calcareous	Alberese	OLn	0.27	431.60	11.50	15.30	n.a.	n.a.	n.a.
		OLv	0.36	345.62	10.36	18.50	n.a.	n.a.	n.a.
		OH	0.79	187.47	10.2	10.80	n.a.	n.a.	n.a.
		A	0.99	111.09	7.64	14.60	5021	571	652
		Bw1	1.45	18.00	0.94	1.40	2688	244	135
		Bw2	1.36	9.32	0.96	0.71	2861	258	122
		Bw3	1.31	16.30	1.13	0.56	5700	233	91
		Bwb	1.28	52.33	0.69	0.34	4356	125	67
	Poggio ai lecci	OL	0.25	453.5	10.50	14.50	n.a.	n.a.	n.a.
		A	1.00	112.46	8.26	15.90	10451	511	668
		AB	1.10	72.26	5.55	5.20	8220	324	363
		BA	1.39	31.98	2.52	1.60	4570	190	222
		Bw	1.44	15.25	1.32	0.65	3323	135	200
		C&Bb	1.34	37.99	0.87	0.36	4165	75	137
	Albatraia	OL/OH	0.32	372.70	12.20	13.80	n.a.	n.a.	n.a.
		A	0.99	110.66	7.46	9.50	9550	574	573
		AB	1.45	18.00	0.94	1.40	2688	244	135

		Bw 1	1.06	18.08	0.75	2.80	141	44	72
		Bw 2	1.54	13.21	0.59	1.50	120	66	53
		Bw 3	1.57	5.69	0.37	1.40	296	130	100
Biotite granite	Is Cannoneris 1	OLn/OLv	0.26	445.37	11.97	14.97	5340	575	620
		OLt	0.53	227.24	12.57	26.23	944	199	203
		OH	1.03	196.89	10.46	13.60	3686	464	363
		A	0.79	113.86	7.34	3.34	3399	433	297
		AB	1.09	69.29	4.03	0.80	3431	394	312
		Bw1	1.44	25.11	1.38	0.66	847	212	169
		Bw2	1.53	11.07	0.71	0.54	381	135	77
		BC	1.53	11.71	0.74	0.42	324	138	88
		C	1.54	9.79	1.05	0.28	368	151	103
	Is Cannoneris 2	OLn/OLv	0.38	399.57	12.03	14.77	5326	722	479
		OLt	0.46	247.86	9.57	22.02	3283	465	405
		OH	1.00	169.10	13.80	22.00	1239	209	341
		E	1.02	62.80	3.82	11.55	3015	417	263
		A	1.00	89.14	5.57	10.40	2474	437	242
		AB	1.25	56.68	2.50	1.80	n.a.	n.a.	n.a.
		Bw1	1.42	26.84	1.50	0.48	2451	357	272
		Bw2	1.51	15.64	0.97	0.32	n.a.	n.a.	n.a.
	Is Cannoneris 3	OLn/OLv	0.36	311.33	10.90	16.47	n.a.	n.a.	n.a.
		OLt/OH	0.86	179.11	10.53	28.15	9959	1215	666

		A	0.98	100.58	6.39	9.73	6522	661	439
		EB	0.96	87.91	5.05	21.60	7023	877	520
		Bw1	1.43	36.14	1.72	0.72	378	134	100
		Bw2	1.38	42.97	2.20	1.47	1509	188	201
		Bw3	1.53	11.89	0.59	0.84	584	120	112
		Cr	1.62	4.15	0.31	n.a.	n.a.	n.a.	n.a.
Granite with quartzite	Sette Fratelli1	OLn/OLv/A	0.51	111.70	6.00	12.20	n.a.	n.a.	n.a.
		A	1.09	94.45	4.73	17.40	4015	467	316
		EB	1.40	71.69	4.38	7.60	1609	207	212
		Bw1	1.55	46.77	2.50	4.60	65	68	25
		Bw2	1.58	11.25	0.72	3.70	186	150	59
		BC	1.61	4.00	0.00	3.20	321	170	70
	Sette Fratelli 2	OLn/OLv/A	0.30	390	14.00	18.90	n.a.	n.a.	n.a.
		OLt	1.00	145	11.00	27.90	9158	1028	861
		A	1.00	122.34	8.77	9.00	7797	693	653
		EB	1.45	41.39	2.37	4.20	2433	255	272
		Bw1	1.51	20.04	1.42	1.00	1336	223	220
		Bw2	1.52	18.28	1.31	0.59	1334	261	200
		Cr	1.57	5.04	0.41	0.48	n.a.	n.a.	n.a.

Table S3. Stocks of C and nutrients both in the fine earth (FE) and skeleton (SK) fractions for each genetic horizon of the soils under Holm oak (*Quercus ilex* L.) stands developed on different parent materials (calcareous, biotite granite, and granite with quartzite veins). Tuscany and Sardinia, Italy.

Parent Material	Profile	Horizon	FE	SK	Stock C FE	Stock C SK	Stock TN FE	Stock TN SK	Stock P_{av} FE	Stock P_{av} SK	Stock Ca_{av} FE	Stock Ca_{av} SK	Stock Mg_{av} FE	Stock Mg_{av} SK	Stock K_{av} FE	Stock K_{av} SK
			%		Mg ha^{-1}				kg ha^{-1}							
Calcareous	Alberese	OLn	100	0	23.43	0.00	0.62	0.00	0.83	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OLv	100	0	24.88	0.00	0.75	0.00	1.33	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OH	100	0	7.41	0.00	0.40	0.00	0.43	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		A	60	40	32.99	0.00	2.27	0.00	4.34	0.00	1491.24	3047.93	169.59	345.62	193.64	14.08
		Bw1	97	3	22.80	0.00	2.35	0.00	1.74	0.00	7003.73	18287.59	631.58	2073.70	298.66	84.45
		Bw2	90	10	17.08	0.00	1.19	0.00	0.60	0.00	5973.6	8127.82	244.18	921.65	95.37	37.53
		Bw3	40	60	66.98	0.00	0.88	0.00	0.44	0.00	5575.68	10159.77	160.00	1152.06	85.76	46.92
	Poggio ai lecci	OL	100	0	34.40	0.00	0.80	0.00	1.10	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		A	50	50	11.25	0.00	0.83	0.00	1.59	0.00	1045.10	1015.98	51.10	115.21	66.80	4.69
		AB	50	50	15.90	0.00	1.22	0.00	1.14	0.00	1808.40	2031.95	71.28	230.41	79.86	9.38
		BA	65	35	22.22	0.00	1.75	0.00	1.11	0.00	3176.15	5079.89	132.05	576.03	154.29	23.46
		Bw	60	40	50.51	0.00	4.38	0.00	2.15	0.00	11005.78	23367.48	447.12	2649.73	662.40	107.91
		C&Bb	40	60	20.36	0.00	0.47	0.00	0.19	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Albatraia	OL/OH	100	0	23.55	0.00	0.77	0.00	0.87	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		A	97	3	54.78	0.00	3.69	0.00	4.70	0.00	4727.25	5079.89	284.13	576.03	283.64	23.46
		AB	97	3	23.49	0.00	1.23	0.00	1.82	0.00	3507.84	9143.80	318.42	1036.85	176.18	42.23
		Bw1	50	50	11.50	0.00	0.48	0.00	1.78	0.00	89.68	6095.86	27.98	691.23	45.79	28.15
		Bw2	50	50	34.57	0.00	1.55	0.00	3.93	0.00	314.16	17271.61	172.79	1958.50	138.75	79.76

		Bw3	40	60	17.87	0.00	1.17	0.00	4.40	0.00	929.44	20319.55	408.20	2304.11	314	93.84
Biotite granite	Is Cannoneris 1	OLn/OLv	100	0	30.59	0.79	0.82	0.04	1.03	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OLt	100	0	7.75	0.20	0.45	0.01	0.92	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OH	100	0	93.62	1.34	4.95	0.07	6.09	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		A	75	25	29.74	1.04	1.92	0.06	0.96	0.00	968.69	18.14	121.31	10.15	82.19	26.92
		AB	80	20	37.76	1.49	2.20	0.08	0.44	0.00	1869.90	25.92	214.73	14.50	170.04	38.45
		Bw1	75	25	68.99	5.54	3.87	0.30	1.76	0.00	1933.38	80.34	491.29	44.96	386.42	119.19
		Bw2	63	37	29.17	4.95	1.80	0.27	1.16	0.00	1035.56	93.30	366.93	52.21	209.29	138.41
		Bw3	60	40	38.38	6.39	2.39	0.35	1.39	0.00	1231.20	129.59	524.40	72.51	334.40	192.23
		Bw4	80	20	23.97	4.75	2.57	0.26	0.76	0.00	900.86	82.93	369.65	46.41	252.14	123.03
	Is Cannoneris 2	OLn/OLv	100	0	84.23	1.78	2.53	0.10	3.11	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OLt	100	0	11.43	0.30	0.46	0.02	1.21	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OH	100	0	58.77	1.09	4.49	0.06	7.51	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		E	88	13	62.59	4.01	3.23	0.22	15.17	0.00	4664.88	69.98	1746.25	39.16	1659.98	103.81
		A	80	20	35.66	1.19	2.23	0.06	4.16	0.00	1006.62	20.73	176.26	11.60	97.89	30.76
		AB	98	3	21.25	0.89	0.94	0.05	0.68	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		Bw1	57	43	84.85	6.73	4.76	0.37	1.55	0.00	9940.37	117.49	2220.20	65.74	2493.80	174.29
		Bw2	45	55	65.81	6.98	3.96	0.38	1.18	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Is Cannoneris 3	OLn/OLv	100	0	33.44	0.89	1.13	0.05	1.73	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OLt/OH	100	0	22.26	0.45	1.24	0.02	3.38	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		A	83	17	39.19	1.19	2.39	0.06	3.37	0.00	1876.88	13.82	182.24	7.73	125.17	20.51
		EB	80	20	42.19	1.49	2.43	0.08	10.34	0.00	3371.04	25.92	420.96	14.50	249.60	38.45

		BW1	70	30	108.52	6.24	5.15	0.34	2.16	0.00	3031.50	25.92	348.50	14.50	197.50	38.45
		Bw2	75	25	35.24	2.08	1.67	0.11	1.53	0.00	1668.25	36.29	209.59	20.30	228.90	53.83
		Bw3	53	47	61.03	9.21	3.18	0.50	2.90	0.00	1817.34	141.68	430.67	79.28	360.17	210.18
		Cr	55	45	13.44	6.68	0.28	0.36	4.07	0.00	633.99	155.51	464.13	87.01	398.59	230.68
Granite with quartzite	Sette Fratelli1	OL/OH/A	100	0	17.06	0.89	0.92	0.05	0.00	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		A	80	20	10.80	0.37	0.63	0.02	0.00	0.00	526.89	3.24	61.17	1.82	41.36	4.81
		EB	80	20	55.66	2.52	2.98	0.14	0.01	0.00	1914.71	22.03	246.33	12.33	252.28	32.68
		Bw1	75	25	47.06	8.02	3.02	0.44	0.02	0.00	272.03	69.98	284.58	39.16	104.63	103.81
		Bw2	75	25	262.50	5.94	1.85	0.32	0.01	0.00	587.76	51.83	474.00	29.00	186.44	76.89
		BC	50	50	6.81	2.97	0.79	0.16	0.01	0.00	516.81	25.92	273.70	14.50	112.70	38.45
	Sette Fratelli 2	OL/A	100	0	35.16	0.89	1.22	0.05	0.00	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		OT	100	0	14.54	0.30	1.06	0.02	0.00	0.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		A	80	20	79.41	2.38	5.54	0.13	0.00	0.00	915.80	2.59	102.80	1.45	86.10	3.84
		EB	60	40	72.01	3.56	4.12	0.19	0.00	0.00	6237.60	20.73	554.40	11.60	522.40	30.76
		Bw1	60	40	81.70	8.02	5.79	0.44	0.00	0.00	4233.42	31.10	443.70	17.40	473.28	46.14
		Bw2	40	60	50.01	5.35	3.58	0.29	0.00	0.00	5446.87	69.98	909.17	39.16	896.94	103.81
		Cr	20	80	11.87	4.46	0.97	0.24	0.00	0.00	3649.82	46.65	714.10	26.10	547.20	69.20

Table S4/a. Results of ANOVA showing the influence of different lithologies on physical and chemical properties of the organic (O), organo-mineral (OM), and mineral (M) tiers, on the element stock per 0.01-m layer of the O, OM, and M tiers, and on the depth layer of soils under Holm oak forests developed on different parent materials (calcareous, biotite granite, and granite with quartzite veins). Tuscany and Sardinia, Italy.

		Tiers				0.01-m layer of the tiers			Depth layer		
Physical and chemical properties					**Element stock**						
			F value	*significance*			*F value*	*significance*		*F value*	*significance*
pH		O	1.7487	n.s.	TOC	O	0.9311	n.s.	Litter	3.175	n.s.
		OM	4.8515	*		OM	0.5351	n.s.	0-0.3 m	2.8187	n.s.
		M	0.5982	n.s.		M	1.4792	n.s.	0.3-0.5 m	1.7818	n.s.
Particle-size distribution	Sand	O	-	-	TN	O	0.5376	n.s.	Litter	3.4345	n.s.
		OM	3.925	*		OM	1.4710	n.s.	0-0.3 m	0.8369	n.s.
		M	13.69	***		M	0.3658	n.s.	0.3-0.5 m	1.3787	n.s.
	Silt	O	-	-	P_{av}	O	1.3875	n.s.	Litter	3.9891	•
		OM	4.3448	*		OM	2.8425	n.s.	0-0.3 m	3.1521	n.s.
		M	63.38	***		M	6.7346	**	0.3-0.5 m	1.8571	n.s.
	Clay	O	-	-	Ca_{av}	O	-	-	Litter	-	-
		OM	0.5977	n.s.		OM	2.2660	n.s.	0-0.3 m	1.617	n.s.
		M	6.6161	**		M	5.3098	*	0.3-0.5 m	1.9505	n.s.
TOC		O	1.5522	n.s.	Mg_{av}	O	-	-	Litter	-	-
		OM	2.2363	n.s.		OM	0.2391	n.s.	0-0.3 m	0.4437	n.s.
		M	1.0821	n.s.		M	0.5359	n.s.	0.3-0.5 m	1.1962	n.s.
TN		O	0.6396	n.s.	K_{av}	O	-	-	Litter	-	-
		OM	4.5691	*		OM	1.0741	n.s.	0-0.3 m	0.557	n.s.
		M	0.0024	n.s.		M	0.2204	n.s.	0.3-0.5 m	0.4089	n.s.

P_{av}	O	1.7334	n.s.
	OM	1.3162	**
	M	4.8377	*

Level of significance: n.s. = not significant, ●= $P \leq 0.1$ * = $P \leq 0.05$, ** = $P \leq 0.01$, *** = $P \leq 0.001$.

TOC = total organic carbon; TN = total nitrogen; P_{av} = available phosphorous; Ca_{av} = available Ca; Mg_{av} = available Mg; K_{av} = available K.

Table S4/b Results of ANOVA showing the influence of calcareous (CA), biotite granite (BG), and granite with quartz veins (GQ) parent materials on physical and chemical properties according to the organic (O), organo-mineral (OM), and mineral (M) tiers, on the element stock per 0.01-m layer of the O, OM, and M tiers, and on the depth layer of soils under Holm oak forests developed on different parent materials (calcareous, biotite granite, and granite with quartzite veins). Tuscany and Sardinia, Italy.

			Parent materials				0.01-m layer			Depth layer	
Physical and chemical properties					**Element stock**						
			F value	*significance*			*F value*	*significance*		*F value*	*significance*
pH		CA	0.1408	n.s.	C	CA	75.04	***	CA	2.0898	n.s.
		BG	3.3514	●		BG	60.919	***	BG	6.3784	*
		GQ	0.5772	n.s.		GQ	6.6333	*	GQ	1.5455	n.s.
Particle size distribution	Sand	CA	14.129	**	TN	CA	13.256	***	CA	5.6150	●
		BG	10.846	**		BG	17.573	***	BG	5.8438	*
		GQ	3.892	●		GQ	7.822	**	GQ	7.2001	●
	Silt	CA	4.8992	*	P_{av}	CA	21.408	***	CA	4.9013	●
		BG	8.0245	*		BG	12.325	***	BG	3.1392	n.s.
		GQ	0.3611	n.s.		GQ	4.1246	*	GQ	3.3268	n.s.
	Clay	CA	10.955	**	Ca_{av}	CA	4.6533	●	CA	0.6035	n.s.
		BG	15.851	**		BG	3.9232	●	BG	6.8881	●
		GQ	13.181	**		GQ	21.795	**	GQ	1.7482	n.s.
TOC		CA	59.752	***	Mg_{av}	CA	6.4277	*	CA	1.3287	n.s.
		BG	35.017	***		BG	5.7396	*	BG	7.0033	●
		GQ	5.3245	*		GQ	39.343	***	GQ	2.0538	n.s.
TN		CA	248.43	**	K_{av}	CA	19.862	***	CA	4.1519	n.s.
		BG	125.39	***		BG	6.0877	*	BG	4.4935	n.s.

	GQ	14.749	**		GQ	8.9291	*	GQ	1.3512	n.s.
P_{av}	CA	46.003	***							
	BG	43.887	***							
	GQ	14.749	***							

Level of significance: n.s. = not significant, ●= $P \leq 0.1$ * = $P \leq 0.05$, ** = $P \leq 0.01$, *** = $P \leq 0.001$.

TOC = total organic carbon; TN = total nitrogen; P_{av} = available phosphorous; Ca_{av} = available Ca; Mg_{av} = available Mg; K_{av} = available K.

References

Brenna, S., Rocca, A., Sciaccaluga, M., Valagussa, M., 2010. Sistema di Monitoraggio della Qualità dei Suoli di Lombardia, Sperimentazione condotta nell'ambito del progetto di ricerca n. 1032 "Sistema di monitoraggio della qualità dei suoli di Lombardia". "Foto a cura di: Marco Sciaccaluga, Alberto Rocca. - SOILQUALIMON" (d.g.r. 22 marzo 2006 n. VIII/2182 – Programma di attività 2006). Quaderni della Ricerca n. 110 - maggio 2010. Regione Lombardia - Direzione Generale Agricoltura U.O. – Ente regionale per i servizi all'agricoltura e alle foreste.

Day, P.R., 1965. Particle fractionation and particle-size analysis. In: Black, C.A., Evans, D.D., Ensminger, L.E., White, J.L., Clarck, F.E. (Eds.), Methods of Soil Analysis. Part 1. Agron. Monogr. 9. ASA and SSSA, Madison, WI, pp. 545–567.

De Nicola, C., Zanella, A., Testi, A., Fanelli, G., Pignatti, S., 2014. Humus forms in a Mediterranean area (Castelporziano Reserve, Rome, Italy): classification, functioning and organic carbon storage. Geoderma 235–236, 90-99. https://doi.org/10.1016/j.geoderma.2014.06.033.

Camponi, L., Cardelli, V., Cocco, S., Serrani, D., Salvucci, A., Cutini, A., Agnelli, A., Fabbio, G., Bertini, G., Roggero, P.P., Corti, G. 2022. Effect of coppice conversion into high forest on soil organic C and nutrients stock in a Turkey oak (*Quercus cerris* L.) forest in Italy. Journal of Environmental Management, 312. *https://doi.org/10.1016/j.jenvman.2022.114935*.

Corti, G., Agnelli, A., Ugolini, F.C., 1997. Release of Al by hydroxy-interlayered vermiculite and hydroxy-interlayered smectite during determination of cation exchange capacity in fine earth and rock fragments fractions. Eur. J. Soil Sci. 48, 249–262. https://doi.org/10.1111/j.1365-2389.1997.tb00545.x

Corti, G., Ugolini, F.C., Agnelli, A., 1998. Classing the soil skeleton (greater than two millimeters): Proposed approach and procedure. Soil Sci. Soc. Am. J. 62, 1620–1629. *https://doi.org/10.2136/sssaj1998.03615995006200060020x*

Garlato, A., Obber, S., Vinci, I., Mancabelli, A., Parisi, A., Sartori, G., 2009a. La determinazione dello stock di carbonio nei suoli del Trentino a partire dalla banca dati della carta dei suoli alla scala 1:250.000. Museo Tridentino di Scienze Naturali. Trento Studi Trent Sci Nat 85, 157–160.

Garlato, A., Obber, S., Vinci, I., Sartori, G., Manni, G., 2009b. Stock attuale di carbonio organico nei suoli di montagna del Veneto. Museo Tridentino di Scienze Naturali. Trento Studi Trent Sci Nat 85, 69–8.

Guermandi, M., Marchi, N., Tarocco, P., Calzolari, C., Ungaro, F., Villani, I., 2013. Siti locali rappresentativi dei suoli della pianura e della collina Emiliano-Romagnola. In: Emilia-Romagna, Regione (Ed.), Servizio Geologico, Sismico e dei Suoli. IRPI CNR, Provincia di Ferrara (41 pp.).

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter, in: Sparks, D., Page, A., Helmke, P., Loeppert, R.H., Soltanpour, P.N. Tabatabai, M.A., Johnston, C.T., Sumner, M.E. (Eds.), Methods of Soil Analysis. SSSA Book Series. https://doi.org/10.2136/sssabookser5.3.c34

Olsen, S.R., Cole, C.V., Watanabe, F.S., Dean, L.A., 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate, USDA. Circular 939

CHAPTER 4 - IMPACT OF THE MANAGEMENT ON FOREST SOC STORAGE CAPACITY IN FINE EARTH, SKELETON AND ROOTS COMPARE TO ABOVEGROUND BIOMASS OF DIFFERENT STAND TYPES

1. Introduction

In view of mitigating greenhouse gas emissions (GHG), forest ecosystems are constituted by natural resources able to sink elements; for that reason, they have been representing important research issues for decades (e.g., Jandl et al., 2007; Shrestha et al., 2015; Li et al., 2018). In order to face future climate challenges, as reported by Giebink et al. (2022), the Oxford University's Nature-based Solutions Initiative estimated a reduction in CO_2 emissions of 10,000 MMT per year through protecting, restoring, and managing sinks. Concerning this function, soil and plants together represent important and widely recognized drivers for carbon sequestration and storage (e.g., Lorenz et al., 2014; Lal et al., 2015; Sadatshojaei et al., 2021), able to guarantee a stable carbon sink through various mechanisms (photosynthesis, roots turnover, microbiological activity, degradation of organic matter, etc.). For example, Wang et al. (2021) studying a planted alpine coniferous forest (*Picea asperata* Mast.) to understand the role of absorptive and transport roots in storing soil carbon, found that the rhizosphere soil C stocks induced by absorptive roots and transport roots play different roles in regulating the total rhizosphere soil C storage in forests. The efficiency of this important function strictly depends on natural aspects and anthropic activities. In fact, woods and forests are exploited all over the world and subjected to different management to provide goods and lands necessary for human sustenance (e.g., MacCleery, 1992; Scarascia-Mugnozza et al., 2000; Messier et al., 2015). Particularly in Europe, the same forest unit has been perceived and utilized historically to solve multiple functions such as hunting, bee-keeping, grazing in forests, forest assortment, wood felling and timber use (Pretzsch et al., 2008). As well as the aboveground also the soil is affected by anthropic activities capable to determine variations in physicochemical and biological properties (soil structure, organic carbon content, biological activity, etc.) (Palese et al., 2014; Wang et al., 2014; de Moraes et al., 2018).

In Italy, forests cover 35% of the land with a remarkable vegetation variability mostly depending on the latitude (INFC 2015). The majority of this afforested territory is located in proximity or in correspondence with the Alps and Apennines, the principal national mountain chains (Lelli et al., 2021). In particular, the Apennines chain, thanks to its latitudinal extension throughout the Italian Peninsula, represents an important reservoir of national forest biodiversity (e.g., Stanisci et al., 2005; Malandra et al., 2019). The most common forest types in the Apennines are broadleaves kenosis, such as oaks forests (e.g., turkey oak (*Quercus cerris* L.), downy oak (*Quercus pubescens* Willd.), and holm oak (*Quercus hilex* L.)), beech (*Fagus sylvatica* L.) forests, and mixed broadleaves forests (e.g., hornbeam (*Ostrya* spp.) and ash tree (*Fraxinus* spp.)), that ensure almost the 46% of national forest biodiversity (INFC 2015).

One of the most important relief included in the Apennines chain of Marche region is the Mount San Vicino. This mountain has hosted human activities since Neolithic and represent a good example of how forest type and management can impact on soil characteristics (Silvestrini et al., 2005). Several environmental aspects of Mount San Vicino were already investigated, like biochemical soil properties under European Beech (*Fagus sylvatica* L.) (De Feudis et al, 2016; Cardelli et al., 2019), soil respiration dynamics in *Bromus erectus*-dominated grasslands (Francioni et al., 2020), the vegetation and plant landscape (Allegrezza, 2003), and other geomorphological issues (e.g., Coltorti et al., 1996; Scisciani et al., 2002). In addition to these valuable studies and considering the challenges related to GHG, the capacity of the principal ecosystems of the Mount San Vicino to stock carbon is a missing important aspect that is worth to assess.

With the present study, we investigated soils (including skeletal fraction), roots (fine to very coarse) and aboveground biomass in twenty assay areas in the Mt. San Vicino, which included four different forest typology stands (beech forests, mixed oak forests, turkey oak forests, and broadleaves mixed forest) subjected to three managements (coppicing, conversion to high stand, and mature high stand). The aim was to assess how forest types and management determine differences in organic carbon storage, considering aboveground biomass, forest floor, mineral soil and fine to very coarse roots within a range of 0-30 cm depth, also the skeletal fraction was taken into consideration as volumetric diluent of the element.

2. Materials and methods

2.1 Study site and stands features

The study area is subdivided into twenty assay areas representative of the four forest types that differs for botanical composition and management. The geomorphology of the area is characterized by the presence of an hilly-mountainous dominant land morphology strongly influenced by the presence of Mt. San Vicino (1479 m a.s.l.) that constitute the higher relief of Marche mountain ridge (Figure 1). The total forest area under study covers a surface of about 1,143 hectares. In the study site the mean annual air temperature (MAAT) ranged from 13.5 to 14.6 °C and the mean annual precipitation (MAP) from 750 to 1139 mm. The soils had developed on calcareous landslides parent materials that were represented by massive limestone, white micritic limestone and red scale limestone. Soil morphologies together with general information about the areas and aboveground cover are reported in Table 1 and 2.

The broadleaves mixed forest assay parcels are located in an area with an altitude between 400 and 1000 m a.s.l.. The mean slope is ranging from 30 to 60 % and the dominant exposure N-NO. The soil cover is about 90% and is mostly represented by hornbeam (*Ostrya carpinifolia* Scop.) with a minor presence of downy oak, Italian maple (*Acer opalus* Mill.) and manna ash (*Fraxinus ornus* L.). The common management of these forests is the coppice-management system for firewood production. The average trees number is about 6578 plants per hectare while the average diameter and the mean basal area are respectively of 7.70 cm and 27.87 $m^2 ha^{-1}$.

The Turkey oak forest assay parcels are located in an area with an altitude between 800 and 1200 m a.s.l.. The mean slope is ranging from 20 to 45 % and the dominant exposure is N-NO. The soil cover is ranging from 40 to 90 % and is mostly represented by Turkey oak with a minor presence of Italian maple, hornbeam and beech. These forests are managed both as coppices and high forest for firewood production. The coppices stands present a tree density of 4260 plants per hectare, 11.43

cm of average diameter and 32.09 m^2 ha^{-1} of mean basal area, while the high stand a tree density of 3060 plants per hectare, 14.77 cm of average diameter and 24.26 m^2 ha^{-1} of mean basal area.

The mixed oak forest assay parcels are located in an area with an altitude between 900 and 1000 m a.s.l.. The mean slope is ranging from 10 to 55 % and the dominant exposure is N-NO. The soil cover is about 70 % and is mostly represented by downy oak with a minor presence of sessile oak (*Quercus ptrea* (Matt.) Liebl.), manna ash, field maple (*Acer campestris* L.) and different species of rowan (*Sorbus* spp.). These forests are managed both as coppices for firewood production and high forest for hydrogeological protection purposes. The coppices stands present a tree density of 2557 plants per hectare, 8.70 cm of average diameter and 15.73 m^2 ha^{-1} of mean basal area, while the high stand a tree density of 1431 plants per hectare, 12.40 cm of average diameter and 25.66 m^2 ha^{-1} of mean basal area.

The beech forest assay parcels are located in an area with an altitude between 900 and 1200 m a.s.l.. The mean slope is ranging from 5 to 80 % and the dominant exposure is N-NO. The soil cover is ranging from 75 to 100 % and is mostly represented by beech with a minor presence of hornbeam, Italian maple, sycamore maple and beech. These forests are subjected to three different management addresses: i) coppices for firewood production; ii) transition forests from coppice to high stand management; iii) high stand forests for both hydrogeological protection and tourist-recreational use. The coppices stands present a tree density of 2752 plants per hectare, 8.07 cm of average diameter and 29.97 m^2 ha^{-1} of mean basal area; the coppices in conversion to high stand a tree density of 3818 plants per hectare, 13.48 cm of average diameter and 45.05 m^2 ha^{-1} of mean basal area, while the high stand a tree density of 1178 plants per hectare, 20.85 cm of average diameter and 40.40 m^2 ha^{-1} of mean basal area.

Figure 1 - Geographical position of Study site and soil profile position

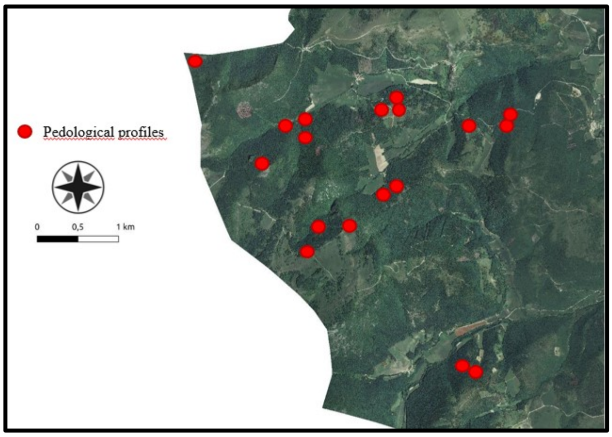


Figure 2 – Detail of the geographical distribution of soil profiles inside the study site

Table 1. General features and averaged morphology of the soils under four forest types (beech, mixed oak, turkey oak and hornbeam-manna ash) and three different managements (coppice, high stand conversion and high stand), according to each soil tier; Mt. San Vicino, Italy. For symbols see legend.

Mean annual air temperature (MAAT) varied from 13.5 to 14.6 °C. Mean annual precipitation (MAP) varied from 750 to 1139 mm. Parent material: rock fall deposit

Tier	Horizons[a]	Depth[b]	Thickness[c]	Boundary[d]	Colour[e]	Texture[f]	Structure[g]	Consistence[h]	Roots[i]	Rock Frags[l]	Other observations[m]
		cm			Moist		Grade Sz Type		Qty Sz	%, by sight	
Forest type: beech *Management:* coppice; *Forest age:* 40 years. *Bedrock:* red scale limestone/whitish micritic limestone; *Mean slope:* 20-60%; *Exposure:* N, NW; *Emerging rock:* 5-30%; *Average soil cover:* 80%. *Soil:* Humic Lithic Eutrudept (Soil Survey Staff, 2014)											
Litter	OLn; OLv; OF; OH	10/2-0	4-6	CW; CS; AS; AW	5YR 3/2	-	3gr	-	3/2vf, f	2	-
Organo-mineral	A; AB; ABb; AE	0-14/2	4-6	CW; CS	5YR 3/1 7.5YR 2.5/2	c	3vf gr; 3vf, f, m sbk, abk	m(fr); m(fi); BR	3vf, f; 2m; 1co, vco	2-50	SL
Mineral	Bw; Bwb; BC	6/36-11/49+	8.5-18	CW; CS	5YR 4/6 10YR 7/3	c	3vf, f, m, c sbk	m(fr); BR; (w)p	2vf, f, m; 1co, vco	5-75	SL; CH; mesofauna; mCAM
Management: coppice in conversion to high stand*;* *Forest age:* 45-70 years. *Bedrock:* red scale limestone; *Mean slope:* 5-50%; *Exposure:* N, NW; *Emerging rock:* 10-20%; *Average soil cover:* 90% *Soil:* Humic Lithic Eutrudept (Soil Survey Staff, 2014)											
Litter	OLn; OLv; OF; OHc	12/1-0	4-7	CW; CS	-	-	3vf, gr	m(fr)	3vf, f	2-5	-
Organo-mineral	A; AB	0-9/2	5-7	CW; CS	5YR 2/2, 3/2 7.5YR 3/2, 3/4	cl	3vf, gr; 3 vf, f, m, co sbk	m(fr); m(fi); BR; (w)p	3vf, f; 2m, co; 1vco	2-20	-
Mineral	Bw; BC; CB	7/44-13/53+	13-17	CW; CB	5YR 4/2, 4/3, 4/4 7.5YR 4/4, 4/6, 6/3 10YR 3/4, 7/3	cl	3gr; 3vf, 2f, m, sbk; 3vf, f, abk	m(fr); m(fi); BR; (w)p	3vf, f; 2m; 1co, vco	30-70	CAM
Management: high stand; *Forest age:* 50-80 years. *Bedrock:* whitish micritic limestone; *Mean slope:* 40-80%; *Exposure:* N; *Emerging rock:* 2-20%; *Average soil cover:* 95-100% *Soil:* Humic Lithic Eutrudept (Soil Survey Staff, 2014)											

Litter	OLn; OLv; OF; OHc	13/1-0	2.5-5	CW; CS; AS; AW	-	-	3vf, f gr	m(fr)	3vf, f; 2 m; 1 co	0-5	Mesofauna
Organo-mineral	A; AB	0-3/7	3-4	CW; CS	5YR 3/2, 3/3 10YR 3/2	c	3vf, f, m sbk, abk	m(vfr); m(fr); m(fi);	3vf, f 1m, co	2-70	Mycelium
Mineral	Bw; BC	0/48-7/54+	12-16	CW; GW	5YR 3/3 10YR 6/3	c	2/3vf, f, m, co, vo sbk, abk	m(vfr); m(fr); BR; (w)ps	2vf, f, m; 1co, vc	15-70	CH

Forest type: mixed oak
Management: coppice; *Forest age:* 25 years.
Bedrock: massive limestone; *Mean slope:* 40-55%; *Exposure:* N, NW; *Average soil cover:* 70%
Soil: Humic Lithic Eutrudept (Soil Survey Staff, 2014)

Litter	OLn; OLv; OF; OHc	11/2-0	4.5-8	CW; AW	-	-	-	-	3vf, f	2	-
Organo-mineral	A	0-3	2-3	CW	5YR 2/2	c	2vf, f, m sbk	m(fr)	3vf, f	20	Mycelium
Mineral	Bw; Bwb; BC; BCb	0/24-4/38+	8-10	CW	5YR 3/4, 4/2 7.5YR 3/4, 4/6	c	3vf, f, m sbk	m(fr); BR; (w)p	3vf, f, m; 1co, vc	10-70	-

Management: high stand; *Forest age:* 60 years.
Bedrock: massive limestone; *Mean slope:* 10-35%; *Exposure:* N; *Emerging rock:* 30%; *Average soil cover:* 70%
Soil: Humic Lithic Eutrudept (Soil Survey Staff, 2014)

Litter	OLn; OLv; OF; OH	8/2-0	4-7	AS; AW; CW	-	-	-	-	3vf, f; 1 vc	0-2	-
Organo-mineral	A	0-6/8	5-11	CI; CW	5YR 3/2 7.5YR 3/2	c	3vf, f sbk	m(fr)	3vf, f; 2m; 1vc	20-25	-
Mineral	Bw; BC	0/6-7/48+	11-15 -	CW	5YR 3/2, 4/4 7.5YR 5/4, 4/2	c	3vf, f, m, co sbk	m(fr)	3vf, f; 1m, co, vc	5-60	CH

Forest type: turkey oak
Management: coppice; *Forest age:* 20 years
Bedrock: whitish micritic limestone; *Mean slope:* 20-35%; *Exposure:* N, N-NE, N-NW, NW; *Emerging rock:* <5%; *Average soil cover:* 70%
Soil: Humic Lithic Eutrudept (Soil Survey Staff, 2014)

Litter	OLn; OLv; OF; OH	3/1-0	1.5-3	CW; AW; AS	5YR 2/2 10YR 2/2	-	- 3gr	m(fr)	3vf, f	0-2	-
Organo-mineral	A; AB	0/2-2/14	3.5-5.5	CW; CB; AW	5YR 3/2 7.5YR 3/2, 4/3 10YR 2/1, 3/2	cl	3gr 3vf, f, m sbk	(w)p; (w)s	3vf, f; 2m	2-20	-
Mineral	ABb; Bw; Bwb; BC; CB	2/30-9/45+	8-11	CW	5YR 3/3, 3/4 7.5YR 4/2, 5/4 10YR 3/2, 4/6	cl	3vf, f, 2m sbk	m(fr); (w)p; (w)s	2vf, f; 1m, co, vc	10-75	Mesofauna; mycelium; SL; mCAM

Management: high stand; *Forest age:* 60 years
Bedrock: whitish micritic limestone; *Mean slope:* 30-40%; *Exposure:* N, NW; *Emerging rock:* -; *Average soil cover:* 90-95%
Soil: Humic Lithic Eutrudept (Soil Survey Staff, 2014)

Litter	OLn; OLv; OF; OH	7/1-0	1.5-2.5	CW; CS	-	-	-	m(fr)	0	-	-
Organo-mineral	A; AB	0/2-0.5/6	2-4	CW; AW	7.5YR 2/2, 3/2 10YR 2/2, 3/2	c	3gr; 3vf, f, m sbk, abk	m(fr); m(fi)	2vf, f; 1m, co	1-20	Mesofauna
Mineral	Bw; Bwb; BC	0.5/40-8/43+	11-13	CW	7.5YR 3/2, 5/6 10YR 3/3, 4/4	c	3vf, f, m sbk, abk	m(fr); m(fi); BR	2vf, f, m; 1co	10-80	SL; mesofauna; bedded CHE

Forest type: hornbeam/manna ash
Management: coppice; *Forest age:* 7-40 years
Bedrock: massive limestone; *Mean slope:* 30-60%; *Exposure:* N, NW; *Emerging rock:* 5-20%; *Average soil cover:* 65%
Soil: Humic Lithic Eutrudept (Soil Survey Staff, 2014)

Litter	OLn; OLv; OF; OH	5/1-0	1.5-3	CW; CB	-	-	3gr	m(fr)	3vf, f; 1co	2-5	-
Organo-mineral	A; AB	0/2-2/6	4.5-7.5	CW; CS	7.5YR 3/2 10YR 2/2, 4/4	c	3vf, f, m sbk	m(fr)	3vf, f; 1m, co	2-5	-

Mineral	ABb; Bw; Bwb; BC; C	0/33-6/48+	8-11	CW	7.5YR 3/4, 4/4 10YR 3/2, 5/4	c	3vf, f, m, co sbk, abk	m(fr); m(fi); BR	3vf, f; 1m, co, vc	2-80	mCAM; SL

[a] designation according to Baize et al. (2008) for organic horizons and to Schoeneberger et al. (2012) for mineral horizons.
[b] numbers separated by slash (/) indicate the range of depths observed in the profiles, while the hyphen (-) means “from (what is before it) to (what is after it)”.
[c] referred to the lowest and highest mean thickness.
[d] A=abrupt, C=clear, G=gradual, D=diffuse; S=smooth, W=weavy, I=irregular, B=broken
[e] moist and crushed, according to the Munsell Soil Color Charts. The reported colours are the extremes for the horizons considered.
[f] c=clay, cl=clay loam
[g] 1=weak, 2=moderate, 3=strong; f=fine, m=medium, co=coarse; gr=granular, abk=angular blocky, sbk=sub-angular blocky. Structures are the extremes for the horizons considered.
[h] m(fr)=friable, m(fi)=firm; BR=brittle; (w)ps=slightly plastic, (w)p=moderately plastic; (w)s=moderately sticky. Rupture resistance is referred to the soil with a moist water state.
[i] 0=absent, 1=few, 2=common, 3=many; vf=very fine, f=fine, m=medium, co=coarse, vc=very coarse. Roots abundances are the extremes for the horizons considered.
[l] rock fragments values are the extremes for the horizons considered.
[m] SL=stone line; CH=charcoal fragments; mCAM=many carbonate masses; CHE=chert

Table 2. Average stand parameters and aboveground biomass of the four forest types (beech, mixed oak, turkey oak and hornbeam-manna ash) and three different managements (coppice, high stand conversion and high stand); Mt. San Vicino, Italy. Numbers in parentheses are standard deviations (n=4 for beech and mixed oak; n=8 for turkey oak and hornbeam/manna ash). For each column within forest type and management, mean values with different letters significantly differ for P ≤ 0.05.

Forest type	Management	Average trees number	Average diameter	Mean basal area	Aboveground biomass	
		n° ha^{-1}	cm	m^2 ha^{-1}	Mg ha^{-1}	
Beech	Coppice	2752 (905)	8.07 (3.45)	29.97 (10.28)	190.77 (149.36)	A
	Conversion	3818 (2766)	13.48 (3.32)	45.05 (12.26)	364.15 (82.76)	
	High stand	1178 (181)	20.85 (4.34)	40.40 (13.21)	483.02 (176.71)	
Mixed oak	Coppice	2557 (314)	8.70 (1.39)	15.73 (6.50)	82.31 (37.79)	B
	High stand	1431 (972)	12.40 (5.61)	25.66 (10.11)	169.04 (82.31)	
Turkey oak	Coppice	4260 (3057)	11.43 (4.57)	32.09 (4.26)	177.76 (38.69)	B
	High stand	3060 (4141)	14.77 (7.01)	24.26 (3.40)	220.11 (118.44)	
Hornbeam/manna ash	Coppice	6578 (1985)	7.70 (1.53)	27.87 (4.39)	144.43 (26.95)	B

Capital letters = comparison among forest types

2.2 Soil trenching, morphological description, sampling, analysis, and stock calculation

In November 2021, a geomorphological and soil survey was conducted in each assay parcel, through the opening of several mini-pits and auger holes, to choose the best and most representative position where to dig the soil profile. After this evaluation, two soil profiles were opened in each assay parcel for a total of forty soil profiles, subdivided into four replicates for beech and mixed oak forests and eight replicates for turkey oak and hornbeam/manna ash forests. Following the protocol reported by Camponi et al. (2022), soil profiles were dug at about 1 m downslope from the trunk of one of the biggest trees indicatives of the forest type, where the stem influence was considered absent. The profile was excavated until the lithic contact or at a depth of ≈ 0.50 m and sampled in large amount (≈ 3 kg) within 30 cm. The litter horizons were morphologically described according to Baize et al. (2008) and sampled on a surface of about 3-4 m^2 around each profile. Organo-mineral and mineral horizons, together with the content of coarse and very coarse particles (e.g. gravels and cobbles), were described by Schoeneberger et al. (2012). Averaged morphologies of sampled soils were reported in Table 1. To establish the soil bulk density and the amount of very fine to very coarse (ø ≤ 10 mm) roots, two horizontal soil cores per each horizon were taken by steel cylinders with a volume of 503 cm^3 (diameter 7.7 cm, height 10.8 cm). Instead, for organic horizons, the bulk density was estimated using the pedotransfer function proposed by De Nicola et al. (2014). Soil and litter samples were stored inside a portable fridge, and, once in the laboratory, were air-dried. Mineral samples collected from soil horizons and soil cores were sieved with a mesh to separate the fine earth (ø < 2 mm) from the skeleton (ø > 2 mm) and maintained at 4°C before the analyses.

2.3 Soil physicochemical analyses, C stock, and aboveground biomass evaluation

Physicochemical properties and organic C stocks in mineral soil (ø < 2 mm) and roots were evaluated in a compositum sample brought from the whole 0-30 cm depth layer, while in the litter a compositum sample were constituted by the different genetic horizons during the description activity. The soil texture was determined by-feel method (Thien, 1979), and pH was determined potentiometrically (1:2.5 v:v). Total organic carbon (TOC) concentration on litter, mineral soil and roots was estimated by K-dichromate digestion, heating the suspension at 180°C for 30 min, following the Walkley-Black method (Nelson and Sommers, 1996). Litter and mineral soil C stock was evaluated following the protocol proposed by Camponi et al. (2022). For roots, TOC stock derives from the mathematical product of roots biomass ($Mgha^{-1}$) and TOC content while, the same procedure was used for aboveground biomass but the C content was extrapolated from INFC (2005) data.

2.4 Data treatment and statistical analysis

The soil profiles showed differences in the sequence of genetic horizons due to its natural variability, for this reason a grouping was made according to their nature: *i*) litter tiers, made of well-expressed OL (OLn and OLv) and OH horizons; *ii*) organo-mineral tiers, grouping A, AB and AE horizons; and *iii*) mineral tiers, formed by ABb, Bw, Bwb BC, BCb, CB, and C horizons (Table 1). The differences among samples were tested by two-way ANOVA. Prior to ANOVA, normality and homoscedasticity of the dataset were assessed using Shapiro-Wilk statistical test and by Levene's test at 5% significance level, respectively. Assumptions were not violated and Duncan's multiple range test was used to determine the significant differences between samples at $P \leq 0.05$.

3. Results

3.1 Morphological and physicochemical soil properties

The studied soils were classified as Humic Lithic Eutrudepts (Soil Survey Staff, 2014) and showed on average to be polycyclic soils dominated by periodic landslide phenomena of calcareous parent rock with a dominant clay to clay-loam textural class (Table 1). The soils developed under beech coppices displayed an average soil cover of 75% with a variable content of skeleton (from 5 to 30%). The forest floor shown a scarce development, with a thickness of 4-6 cm while organo-mineral and mineral horizons had an average thickness of 4-6 cm and 8.5-18 cm, respectively. Structure in the organo-mineral horizons was strongly developed and organized into granular to angular blocks, while in the mineral horizons it was strongly developed into sub-angular blocks. Roots were generally abundant all along the soil profile with an increasing dimensional trend. Soil skeleton amount was 40% on average and generally increased with depth. Most of the mineral horizons shown a diffuse presence of centimetric charcoal fragments and in situ calcium carbonate resettlement (secondary carbonates).

The beech high stand conversion sites showed a soil cover of 90% on average and that was partly due to rock fragments (10-20%). The litter layer was poorly developed (4-7 cm) with a diffuse presence of hyphae; the thickness of the organo-mineral horizons ranged from 5 to 7 cm, while that of the mineral horizons was from 13 to 17 cm. The soil structure consisted of strongly developed granules in OH horizons of the litter layer, strongly developed granulaes and sub-angular blocks in the organo-mineral horizons, and strongly developed granules and to angular/sub-angular blocks in the mineral horizons. Very fine and fine roots were generally many all along the soil profile, while the abundance of medium and very coarse ones where less expressed (very few to common). As a whole, the soil skeleton amounted to 2-70% and increased with depth. As in the beech coppices sites also in this thesis of charcoal fragments and secondary carbonates were found in abundant amount.

The soils under beech high stand showed a soil surface covered mainly by leaves and coarse woody debrish of variable dimension, while rock fragments covered a variable surface from 2 to 20 %. In addition, there were many (50 per hectare) remains of charcoal kilns and a diffuse presence of hyphae along the soil profile. The litter layer was quite well developed (2.5-5 cm thickness) with noticeable mesofauna activity signs; the organo-mineral horizons were 3-4 cm thick while the mineral horizons had a thickness from 12 to 16 cm. The OH horizon showed a well-developed granular structure with very fine and fine aggregates, the organo-mineral horizons had a strongly developed sub-angular to angular blocky (from very fine to medium) structure, while the mineral horizons displayed a moderately to strongly developed angular and sub-angular blocky structure with coarser aggregates. All the soil tiers showed a poor to abundant amount of roots ranging in size from very fine to very coarse with a decreasing gradient along the profile. Soil skeleton was abundant, on average amounting to 10-70%, generally increasing with depth.

The soils under mixed oak stands managed as coppices showed a soil cover ranging from 60 to 80% minimally (maximum 10%) due to rock fragments (pebbles and cobbles). The litter layer was poorly developed with a thickness of 4.5-8 cm; the thickness of the organo-mineral horizons ranged from 2 to 3 cm, while that of the mineral horizons was from 8 to 10 cm. In litter and in organo-mineral tiers were noticed fungi activity (hyphae). The soil structure was moderately developed in very fine to medium sub-angular blocks in the organo-mineral horizons and strongly developed in very fine to medium sub-angular blocks in the mineral horizons. Very fine and fine roots were generally many all along the soil profile while the abundance of coarse ones where less expressed (very few). As a whole, the soil skeleton amounted to 2-70% and increased with depth.

The mixed oak high stand sites showed an average soil cover of 70% with an amount of 30% of rock fragments. The litter layer was poorly developed with a thickness of 4-7 cm; the thickness of the organo-mineral horizons ranged from 5-11 cm, while that of the mineral horizons was from 11 to 15 cm. The soil structure consisted of strongly developed very fine to fine sub-angular blocks in the organo-mineral horizons and strongly to weak developed very fine to very coarse sub-angular blocks in the mineral horizons. Very fine and fine roots were generally many all along the soil profile while the abundance of medium and very coarse ones where less expressed (very few to common). As a whole, the soil skeleton amounted to 2-60% increasing with depth. Charcoal fragments were found in considerable amount in mineral horizons.

The soils developed under turkey oak coppices displayed an average soil cover of 80-90% with a negligible contribution of emerging rock (<5%). The forest floor shown a scarce development, with a thickness of 1.5-3 cm while organo-mineral (sometime interrupted) and mineral horizons had an average thickness of 3.5-5.5 cm and 8.5-18 cm, respectively. The organic horizons (particularly OH) showed a strongly developed granular structure; organo-mineral horizons showed a strongly developed granular to angular structure while in the mineral horizons it is strongly developed in sub-angular blocky. Very fine and fine roots were generally abundant all along the soil profile while medium, coarse and very coarse ones showed a common to scarce presence. Soil skeleton amount ranged from absent to 75% on average, and generally increased with depth. Most of the mineral horizons shown a diffuse presence of hyphae and secondary carbonates.

The turkey oak high stand sites showed an average soil cover of 90-95%. The litter layer was poorly developed with a thickness of 1.5-2.5 cm; the thickness of the organo-mineral horizons ranged from 2 to 4 cm, while that of the mineral horizons was from 11 to 13 cm. The soil structure consisted of well-developed granular and very fine to medium sub-angular blocks in the organo-mineral horizons and strongly developed very fine to medium sub-angular and angular blocks in the mineral horizons. Very fine and fine roots were generally common all along the soil profile while the abundance of medium and coarse ones where less expressed. As a whole, the soil skeleton amounted to 1-80% increasing with depth.

The soils under hornbeam and manna ash coppices showed an average soil cover of 65% with a contribution (5-20%) due to emerging rock and skeleton fragments (pebbles and cobbles). The litter layer was poorly developed with a thickness of 1.5-3 cm in some case with sporadic presence of OLn horizon; the thickness of the organo-mineral horizons ranged from 4.5 to 7.5 cm, while that of the mineral horizons was from 8 to 11 cm. The soil structure was well-developed in granular aggregates in OH horizon of litter tier, very fine to medium sub-angular blocks in the organo-mineral horizons and strongly developed in very fine to medium sub-angular and angular blocks in the mineral horizons. Very fine and fine roots were generally many all along the soil profile while the abundance of medium, coarse and very coarse ones where less expressed (very few). As a whole, the soil skeleton amounted to 2-80% and increased with depth.

Table 3. Mean values of bulk density, litter depth, skeleton, root biomass, pH, and total organic carbon (TOC) of the soils under four forest types (beech, mixed oak, turkey oak and hornbeam-manna ash) and three different managements (coppice, high stand conversion and high stand); Mt. San Vicino, Italy. Numbers in parentheses are the standard deviations (n=4 for beech and mixed oak; n=8 for turkey oak and hornbeam/manna ash). For each column within forest type and management, mean values with different letters significantly differ for P ≤ 0.05. Box without explicit statistical treatment showed equal significance.

Forest type	Management	Bulk density	Litter depth		Skeleton	Root biomass	pH		TOC		
							Litter	0-30 cm	Litter	0-30 cm	Roots
		kg dm^{-3}	cm		%	Mg ha^{-1}			g kg^{-1}		
Beech	Coppice	1.09 (0.06)	7.00 (3.50)	A	38 (11)	57.22^{a} (11.65)	6.37^{ab} (0.25)	7.51 (0.33)	393.17 (37.40)	61.31 (20.41)	380.41 (14.31)
	Conversion	1.12 (0.10)	6.30 (4.6)		33 (4)	47.95^{ab} (33.40)	6.30^{ab} (0.28)	7.72 (0.12)	360.82 (67.21)	48.48 (6.35)	359.96 (76.82)
	High stand	1.00 (0.04)	6.50 (4.80)		34 (9)	22.77^{ab} (14.44)	6.02^{ab} (0.42)	6.56 (1.60)	361.91 (73.76)	32.43 (9.79)	366.34 (92.38)
Mixed oak	Coppice	0.93 (0.08)	7.50 (3.30)	A	43 (3)	49.46^{ab} (37.26)	5.97^{b} (0.28)	7.66 (0.15)	451.27 (42.13)	58.04 (19.27)	325.34 (42.08)
	High stand	1.07 (0.02)	6.30 (1.70)		38 (3)	15.49^{b} (7.60)	6.46^{a} (0.06)	7.76 (0.17)	377.07 (48.65)	41.76 (15.25)	329.44 (44.50)
Turkey oak	Coppice	1.06 (0.09)	2.60 (1.50)	B	34 (10)	13.75^{b} (7.64)	6.18^{ab} (0.32)	7.65 (0.27)	380.21 (49.70)	70.61 (29.54)	327.48 (37.57)
	High stand	1.02 (0.09)	3.60 (2.30)		47 (10)	55.24^{ab} (57.65)	6.07^{ab} (0.43)	7.55 (0.22)	416.78 (101.02)	68.36 (30.70)	299.37 (78.98)
Hornbeam/manna ash	Coppice	0.99 (0.12)	3.00 (1.20)	B	31 (14)	56.91^{ab} (42.82)	6.10^{ab} (0.32)	7.47 (0.41)	337.14 (113.28)	54.93 (23.94)	304.96 (49.36)

Capital letters = comparison among forest types
Lowercase letters = comparison among management
Superscript letters = interaction between forest types and management

Table 4. Organic carbon stock in aboveground biomass, litter, 0-30 cm mineral layers, and roots collected in 0-30 cm soil layer under four forest types (beech, mixed oak, turkey oak and hornbeam-manna ash) and three different managements (coppice, high stand conversion and high stand); Mt. San Vicino, Italy. Numbers in parentheses are the standard deviations (n=4 for beech and mixed oak; n=8 for turkey oak and hornbeam/manna ash). For each column within forest type and management, mean values with different letters significantly differ for P ≤ 0.05.

Forest type	Management	OC stock					
		Aboveground biomass		Litter		0-30 cm	Roots
		Mg ha^{-1}					
Beech	Coppice	100.15 (78.41)	A	223.25 (128.25)	A	107.77 (18.04)	21.84^{a} (5.03)
	Conversion	191.18 (43.45)		187.34 (161)		88.44 (11.9)	17.16^{ab} (12.95)
	High stand	253.59 (92.77)		196.34 (178)		72.3 (24.65)	8.64^{ab} (5.77)
Mixed oak	Coppice	44.45 (20.40)	B	284.98 (141.85)	A	93.12 (31.58)	15.32^{ab} (9.76)
	High stand	91.28 (44.45)		184.38 (56.92)		83.95 (35.12)	4.98^{b} (2.34)
Turkey oak	Coppice	97.77 (21.28)	B	79.48 (52.19)	B	107.26 (46.44)	4.37^{b} (2.45)
	High stand	121.06 (65.14)		132.54 (107.69)		105.5 (35.6)	18.94^{ab} (22.63)
Hornbeam/Manna ash	Coppice	75.82 (14.15)	B	80.81 (42.09)	B	94.47 (33.5)	16.21^{ab} (8.66)

Capital letters = comparison among forest types
Lowercase letters = comparison among management
Superscript letters = interaction between forest types and management

3.2 Soil physicochemical properties and C stocks

Bulk density and skeleton content showed no differences among thesis while the highest values of roots biomass (57.22 $Mgha^{-1}$) were recorded in the beech coppices and the lowest ones in mixed oak high stands (15.49 $Mgha^{-1}$) and turkey oak coppices (13.75 $Mgha^{-1}$). In terms of aboveground biomass, the highest amount were recorded on average in beech stands (345.98 $Mgha^{-1}$) while the other type showed similar values that ranged from 125.68 to 170.00 $Mgha^{-1}$ (Table 2 and 3).

Forest floor showed a slightly acid reaction with values between 5.97 and 6.46 while mineral soil had greater pH values near the neutrality (6.56-7.76) with differences in the interaction between management and cover typology for the litter layer (Table 3). In particular mixed oak high stand thesis showed the highest pH values (6.46) while mixed oak coppice thesis showed the lowest pH values (5.97). In general TOC contents in litter and 0-30 cm depth layers and in the roots showed no differences among the theses. (Table 3).

The C stock at fixed depth of 30 cm in mineral soil showed similar values in the four theses while differences, in terms of typology, management and interaction between both the variables, were noticed in the aboveground biomass, litter and in the roots biomass (Table 3 and 4).

The aboveground biomass showed the highest values in the beech forests, due to the presence of conversion parcels that rise up the mean values, with an average value of 345.98 $Mgha^{-1}$, while the other stand type showed similar average values respectively of 125.68, 170.00 and 144.43 $Mgha^{-1}$ for mixed oak, turkey oak and hornbeam and manna ash forests. The interaction between the two variables (cover typology and management) showed the highest amount of biomass in beech conversion to high stand and high stand forests compared to the others with a respectively amount of 364.15 and 483.02 $Mgha^{-1}$, while the other forests showed similar values that ranging from 82.31 to 190.77 $Mgha^{-1}$. The aboveground biomass C stock follow the same pattern with the highest values in terms of typology in the beech forests (average of 181.64 $Mgha^{-1}$) and the highest values considering the interaction typology-management in beech conversion to high stand and high stand areas with respectively values of 191.18 and 253.59 Mgha^{-1} while all the other forests showed values that ranging from 44.45 to 100.15 Mgha^{-1} (Table 3 and 4).

The litter layer showed significant differences in relation with forest cover typology, thus the highest values were recorded in beech and mixed oak stands (202.31 and 263.66 Mgha^{-1}) and the lowest under turkey oak and hornbeam/manna ash covers (106.10 and 80.81 Mgha^{-1}).

The differences in roots biomass and organic C stock showed significancy only for the interaction cover typology-management with the highest amounts in beech coppices (57.22 and 21.84 Mgha^{-1} respectively) while the lowest in mixed oak high stands and turkey oak coppices with an amount of respectively 15.49 and 4.98 37 Mgha^{-}1 and 13.75 and 4.37 Mgha^{-1} (Table 3 and 4).

4. Discussion

A study conducted by Eisalou et al., (2013) highlighted how different forest species, in particular beech and oak, influenced forest floor pH, as well as Corti et al. (2019), studying a turkey oak forest, demonstrated how the strict site-plant relation is able to influence the leaves leachate pH. This phenomenon is similar to that observed in the studied mixed oak forests, where the specific composition of the canopy, mostly represented by different broadleaved species, and the site-plant relation could have influenced the litter pH, that showed higher values in the high stands management (6.46) compared to the coppices (5.97).

Previous works focused on the C and nutrients storage capacity in mineral soil (0 to 30 cm or deeper) under pluri-secular managed national forests (Camponi et al., 2022, 2023) found a similar phenomenon to that observed in this case-study, namely the influence of long-lasting (millennia) stand management, which has the same weight as soil forming forces as the forest cover, with the effect obliterating the recent management changes. This hypothesis found strength in field observations like charcoal kilns widespread in all the areas, which testified a previous coppices management or the presence of deep soil horizons with a very dark colour enriched in organic matter, maybe related to past agro-silvo-pastoral activities (Table 1).

Studying pure and mixed beech and oak (*Quercus petraea* (Matt.) Liebl. and *Quercus robur* L.) stands, Pretzsch et Al., (2013) hypothesized that litterfall productivity and degradation rates could vary in relation to the botanical composition. A similar pattern was observed in our study areas where the litter amount and organic C stock was directly related to the thickness of the layers that resulted higher in beech coppices (50-95% of the botanical composition) and mixed oak high stands than in turkey oak coppices. where the botanical composition showed a not negligible amount of secondary tree species in the dominated layers. Furthermore, nutrient contents and particularly C:N ratio were influent parameters on litterfall degradation rates and, considering previous studies (e.g., Langenbruch et al., 2012; Čiuldienė et al, 2017; Jurkšienė et al., 2017; Cardelli et al., 2019; Camponi et al., 2022) beech litterfall tends to have higher values (29.9-70.5) of C:N compared to other oak species including the turkey oak (25.3-68.4). This feature could justify the highest thickness and consequently organic C stock detected under beech coppices parcels.

Roots organic C storage suggested a correlation with roots biomass, since the majority of roots sampled under beech, mixed oak, and turkey oak forests had diameters of 2-5 mm and a similar relation with canopy management to that studied by Van Hees & Clerkx (2003), Montagnoli et al. (2012), and Di Iorio et al. (2013). The cited authors noticed a higher biomass amount of $ø < 5$ mm roots under beech forests compared to other species and an increasing amount of $2 < ø < 5$ mm roots biomass under coppice management. Furthermore, it was observed by Loh et al. (2003) and Puhe et al. (2003) how roots architecture reacted to soil stoniness in terms of biomass amount and vertical deepening, highlighting the fostering of roots development and the reduction of deepening with an increasing skeleton content. Thus, the presence of stone lines between 6 and 11 cm depth, elevated soil stoniness (up to 75%), and shallow soils (BC horizon with crushed rock at 29 cm depth) under beech coppices might induce the concentration of the entire root apparat in the sampling soil volume, inducing to assess that parcels the richest in roots biomass.

Aboveground biomass and consequently aboveground C stock seemed to follow a site-specific and management-influenced pattern, with the highest values in beech coppices in conversion to high forest and high stand. To support this hypothesis, in Ciancio et al., (2006) study results highlighted the positive effect on mean stem volume due to the highest diameter increment in coppiceshigh stand conversion. In addition, Jacob et al., (2010) suggested that above-ground net primary production in mature temperate deciduous forest stands majorly depended on climatic and edaphic factors than on tree species diversity.

5. Conclusions

The observation on soil feature and amount of organic C stock in aboveground biomass, litter, mineral soil and roots within a depth of 30 cm emphasize a common pattern based on three fundamental elements: plant-site relation, stand biological characteristics and management practices. Litter pH seems to be influenced by the plant-site relation and botanical composition, while the different forest floor organic C stock among the stands depends on litter chemical features and botanical composition. In particular the higher presence of beech than other species and C:N ratio of its litter could have influenced the degradation rate fostering the accumulation. Organic C stock in mineral layers seems to follow a pattern already observed in other forests where the long-lasting management, testified here by past charcoal kilns widespread in the area, and vegetation cover represent the major pedogenesis forces in determine organic C stock. Roots biomass seems to be influenced by management and soil characteristics: in beech coppices the harvest activity foster the production of roots with a diameter <5mm and the soil stoniness influence the architecture of roots apparatus that is concentrated in the soil upper part (0-30 cm). To explain the aboveground biomass and C stock variability the main hypothesis is reconducted to a site-management influence pattern led by a combination of the conversion to high stand effect with particular edaphic conditions. The present study further highlights the role of management in conditioning the soil and plants organic C stock in Apennines forest ecosystems characterized by a secular history of exploitation.

References

Allegrezza, M., 2003. Vegetazione e paesaggio vegetale della dorsale del Monte San Vicino (Appennino centrale). Fitosociologia 40(1), 3-118.

Baize, D., Girard, M.C., 2008. Référentiel Pedologique, Edition Quæ. Association francaise pour l'etude du sol (Afes), Versailles, France.

Camponi, L., Cardelli, V., Cocco, S., Serrani, D., Salvucci, A., Cutini, A., Agnelli, A., Fabbio, G., Bertini, G., Roggero, P.P., Corti, G., 2022. Effect of coppice conversion into high forest on soil organic C and nutrients stock in a Turkey oak (*Quercus cerris* L.) forest in Italy. J. Environ. Manag. 312. https://doi.org/10.1016/j.jenvman.2022.114935

Cardelli, V., De Feudis, M., Fornasier, F., Massaccesi, L., Cocco, S., Agnelli, A., Weindorf, D.C., Corti, G., 2019. Changes of topsoil under *Fagus sylvatica* along a small latitudinal-altitudinal gradient. Geoderma 344, 164-178. https://doi.org/10.1016/j.geoderma.2019.01.043

Ciancio, O., Corona, P., Lamonaca, A., Portoghesi, L., Travaglini, D., 2006. Conversion of clearcut beech coppices into high forests with continuous cover: A case study in central Italy. For. Ecol. Manage. 224, 235–240. https://doi.org/10.1016/j.foreco.2005.12.045

Čiuldienė, D., Aleinikovienė, J., Muraškienė, M., Marozas, V., Armolaitis, K., 2017. Release and retention patterns of organic compounds and nutrients after the cold period in foliar litterfall of pure European larch, common beech and red oak plantations in Lithuania. Eurasian Soil Sci. 50, 49–56. https://doi.org/10.1134/S1064229316110028

Coltorti, M., Farabollini, P., Gentili, B., Pambianchi, G., 1996. Geomorphological evidence for anti-Apennine faults in the Umbro-Marchean Apennines and in the peri-Adriatic basin, Italy. Geomorphology 15(1), 33-45. *https://doi.org/10.1016/0169-555X(95)00117-N*

Corti, G., Agnelli, A., Cocco, S., Cardelli, V., Masse, J., Courchesne, F., 2019. Soil affects throughfall and stemflow under Turkey oak (Quercus cerris L.). Geoderma 333, 43–56. https://doi.org/10.1016/j.geoderma.2018.07.010

De Feudis, M., Cardelli, V., Massaccesi, L., Lagomarsino, A., Fornasier, F., Westphalen, D.J., Cocco, S., Corti, G., Agnelli, A., 2017. Influence of altitude on biochemical properties of European Beech (*Fagus sylvatica* L.) forest soils. Forests 8, 213. https://doi.org/10.3390/f8060213

De Moraes Sá, J.C., Potma Gonçalves, D.R., Ferreira, L.A., Mishra, U., Inagaki, T.M., Ferreira Furlan, F.J., Moro, R.S., Floriani, N., Briedis, C., de Oliveira Ferreira, A., 2018. Soil carbon fractions and biological activity based indices can be used to study the impact of land management and ecological successions. Ecol. Indic. 84, 96–105. https://doi.org/https://doi.org/10.1016/j.ecolind.2017.08.029

De Nicola, C., Zanella, A., Testi, A., Fanelli, G., Pignatti, S., 2014. Humus forms in a Mediterranean area (Castelporziano Reserve, Rome, Italy): classification, functioning and organic carbon storage. Geoderma 235–236, 90-99. https://doi.org/10.1016/j.geoderma.2014.06.033

Di Iorio, A., Montagnoli, A., Terzaghi, M. et al. Effect of tree density on root distribution in Fagus sylvatica stands: a semi-automatic digitising device approach to trench wall method. Trees 27, 1503–1513 (2013). https://doi.org/10.1007/s00468-013-0897-6

Eisalou, H.K., Şengönül, K., Gökbulak, F., Serengil, Y., Uygur, B., 2013. Effects of forest canopy cover and floor on chemical quality of water in broad leaved and coniferous forests of Istanbul, Turkey. For. Ecol. Manage. 289, 371–377. https://doi.org/10.1016/j.foreco.2012.10.031

Francioni, M., Trozzo, L., Toderi, M., Baldoni, N., Allegrezza, M., Tesei, G., Kishimoto-Mo, A.W., Foresi, L., Santilocchi, R., D'Ottavio, P, 2020. Soil respiration dynamics in *Bromus erectus*-

dominated grasslands under different management intensities. Agriculture 10, 9. https://doi.org/10.3390/agriculture10010009

Giebink, C.L., Domke, G.M., Fisher, R.A., Heilman, K.A., Moore, D.J.P., Derose, J.R., Evans, M.E.K., 2022. The policy and ecology of forest-based climate mitigation: challenges, needs, and opportunities. Plant Soil 479, 25-52. https://doi.org/10.1007/s11104-022-05315-6

Gee, G.W., Or, D., 2002. Particle-Size Analysis. In Methods of Soil Analysis (eds J.H. Dane and G. Clarke Topp). https://doi.org/10.2136/sssabookser5.4.c12

Jacob, M., Leuschner, C. & Thomas, F.M. Productivity of temperate broad-leaved forest stands differing in tree species diversity. Ann. For. Sci. 67, 503 (2010). https://doi.org/10.1051/forest/2010005

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D.W., Minkkinen, K., Byrne, K.A., 2007. How strongly can forest management influence soil carbon sequestration? Geoderma 137, 253–268. https://doi.org/https://doi.org/10.1016/j.geoderma.2006.09.003

Jurkšienė, G., Janušauskaitė, D., Armolaitis, K., Baliuckas, V., 2017. Leaf litterfall decomposition of pedunculate (Quercus robur L.) and sessile (Q. petraea [Matt.] Liebl.) oaks and their hybrids and its impact on soil microbiota. Dendrobiology 78, 51–62. https://doi.org/10.12657/denbio.078.006

Lal, R., 2005. Forest soils and carbon sequestration. For. Ecol. Manage. 220, 242–258. https://doi.org/https://doi.org/10.1016/j.foreco.2005.08.015

Langenbruch, C., Helfrich, M., Flessa, H., 2012. Effects of beech (*Fagus sylvatica*), ash (*Fraxinus excelsior*) and lime (*Tilia* spec.) on soil chemical properties in a mixed deciduous forest. Plant Soil 352, 389–403. https://doi.org/10.1007/s11104-011-1004-7

Lelli, C., Nascimbene, J., Alberti, D., Agostini, N., Zoccola, A., Piovesan, G., Chiarucci, A., 2021. Long-term changes in Italian mountain forests detected by resurvey of historical vegetation data. J. Veg. Sci. 32, 1–11. https://doi.org/10.1111/jvs.12939

Li, Y., Hu, S., Chen, J., Müller, K., Li, Y., Fu, W., Lin, Z., Wang, H., 2018. Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: a review. J. Soils Sediments 18, 546–563. https://doi.org/10.1007/s11368-017-1906-y

Loh, F.C.W., Grabosky, J.C., Bassuk, N.L., 2003. Growth response of Ficus benjamina to limited soil volume and soil dilution in a skeletal soil container study 53–62.

Lorenz, K., Lal, R., 2014. Soil organic carbon sequestration in agroforestry systems. A review. Agron. Sustain. Dev. 34, 443–454. https://doi.org/10.1007/s13593-014-0212-y

MacCleery, D.W., 1992. Forests - A history of resilience and recovery. United States Department of Agriculture (USDA), Forest Service FS-540, in cooperation with Forest History Society, Durham, North Carolina.

Malandra, F., Vitali, A., Urbinati, C., Weisberg, P.J., Garbarino, M., 2019. Patterns and drivers of forest landscape change in the Apennines range, Italy. Reg Environ Change 19, 1973–1985. https://doi.org/10.1007/s10113-019-01531-6

Messier, C., Puettmann, K., Chazdon, R., Andersson, K.P., Angers, V.A., Brotons, L., Filotas, E., Tittler, R., Parrott, L., Levin, S.A., 2015. From management to stewardship: viewing forests as complex adaptive systems in an uncertain world. Cons. Letters J. Soc. Cons. Biol. 8(5), 368–377.

Montagnoli, A., Terzaghi, M., Di Iorio, A. et al. Fine-root morphological and growth traits in a Turkey-oak stand in relation to seasonal changes in soil moisture in the Southern Apennines, Italy. Ecol Res 27, 1015–1025 (2012). https://doi.org/10.1007/s11284-012-0981-1

Nelson, D.W., Sommers, L.E., 1996. Total Carbon, Organic Carbon, and Organic Matter, in Sparks, D., Page, A., Helmke, P., Loeppert, R.H., Soltanpour, P.N. Tabatabai, M.A., Johnston, C.T., Sumner, M.E. (Eds.), Methods of Soil Analysis. SSSA Book Series. https://doi.org/10.2136/sssabookser5.3.c34

Palese, A.M., Vignozzi, N., Celano, G., Agnelli, A.E., Pagliai, M., Xiloyannis, C., 2014. Influence of soil management on soil physical characteristics and water storage in a mature rainfed olive orchard. Soil Tillage Res. 144, 96–109. https://doi.org/https://doi.org/10.1016/j.still.2014.07.010

Pretzsch, H., Bielak, K., Block, J., Bruchwald, A., Dieler, J., Ehrhart, H.P., Kohnle, U., Nagel, J., Spellmann, H., Zasada, M., Zingg, A., 2013. Productivity of mixed versus pure stands of oak (Quercus petraea (Matt.) Liebl. and Quercus robur L.) and European beech (Fagus sylvatica L.) along an ecological gradient. Eur. J. For. Res. 132, 263–280. https://doi.org/10.1007/s10342-012-0673-y

Pretzsch, H., Grote, R., Reineking, B., Rötzer, T., Seifert, S., 2008. Models for forest ecosystem management: A European perspective. Ann. Bot. 101, 1065–1087. https://doi.org/10.1093/aob/mcm246

Puhe, J., 2003. Growth and development of the root system of Norway spruce (*Picea abies*) in forest stands-a review 175.

Sadatshojaei, E., Wood, D.A., Rahimpour, M.R., 2021. Potential and Challenges of Carbon Sequestration in Soils, in: Applied Soil Chemistry. John Wiley & Sons, Ltd, pp. 1–21. https://doi.org/https://doi.org/10.1002/9781119711520.ch1

Scarascia-Mugnozza, G., Oswald, H., Piussi, P., Radoglou, K., 2000. Forests of the Mediterranean region: gaps in knowledge and research needs. Forest Ecol. Manag. 132(1), 97-109. https://doi.org/10.1016/S0378-1127(00)00383-2.

Scisciani, V., Tavarnelli, E., Calamita, F., 2002. The interaction of extensional and contractional deformations in the outer zones of the Central Apennines, Italy. J. Struct. Geol. 24(10), 1647-1658. https://doi.org/10.1016/S0191-8141(01)00164-X

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Soil Survay Staff, 2012. Field Book for Describing and Sampling Soils, Version 3.0. https://doi.org/10.1038/258254a0

Shrestha, R.K., Strahm, B.D., Sucre, E.B., 2015. Greenhouse gas emissions in response to nitrogen fertilization in managed forest ecosystems. New For. 46, 167–193. https://doi.org/10.1007/s11056-014-9454-4

Silvestrini, M., Carlini, C., Cilla, G., Foglini, L., 2005. Il Neolitico di Matelica, località Braccano : nuovi dati dai recenti scavi /., in: Atti della XXXVIII Riunione scientifica : preistoria e protostoria delle Marche : Portonovo, Abbadia di Fiastra, 1-5 ottobre 2003 : vol. I-II. Istituto italiano di preistoria e protostoria, Firenze.

Stanisci, A., Pelino, G., Blasi, C., 2005. Vascular plant diversity and climate changein the alpine belt of the central Apennines (Italy). Biodiv. Cons. 14,1301–1318. https://doi.org/https://doi.org/10.1007/s10531-004-9674-6

Thien, S.J. (1979), A flow diagram for teaching texture-by-feel analysis. Journal of Agronomic Education, 8: 54-55. https://doi.org/10.2134/jae.1979.0054

Van Hees, A.F.M., Clerkx, A.P.P.., 2003. Shading and root–shoot relations in saplings of silver birch, pedunculate oak and beech. For. Ecol. Manage. 176, 439–448. https://doi.org/https://doi.org/10.1016/S0378-1127(02)00307-9

Wang, Q., Zhang, Z., Guo, W., Zhu, X., Xiao, J., Liu, Q., Yin, H., 2021. Absorptive and transport roots differ in terms of their impacts on rhizosphere soil carbon storage and stability in alpine forests. Soil Biol. Biochem. 161, 108379. https://doi.org/https://doi.org/10.1016/j.soilbio.2021.108379

Wang, X., Vandenbygaart, A.J., McConkey, B.C., 2014. Land Management History of Canadian Grasslands and the Impact on Soil Carbon Storage. Rangel. Ecol. Manag. 67, 333–343. https://doi.org/https://doi.org/10.2111/REM-D-14-00006.1

Appendix – Supplementary data

Table S1 - General features of the study sites and morphology of the profiles opened at each site under different stands in Mt. San Vicino site, Italy. For symbols see legend.

Horizon[a]	Depth	Thickness	Boundary[b]	Color[c]	Structure[f]	Consistence[g]	Textural class[e]	Roots[h]	Skeleton[d]	Other observations
	cm								%	
Plot L26c/Profile 1 (Gauss Boaga Rome 40 4794678 N, 2366633 E) Slope 35%; Exposure NO. Altitude: 630-785 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Turkey oak productive coppice (47 y). Presence of a charcoal kiln (3). Emerging rock: 5%. Soil cover: 90%. Vegetation. Trees: *Quercus cerris* L. 90%, *Ostrya carpinifolia* Scop. 40%, *Quercus pubescens* Willd. 30%, *Fraxinus ornus* L. 15%, *Sorbus aria* L. 15%. Bushes: *Juniperus communis* L. 40%, *Cornus mas* L.25%, *Rubus ulmifolius* L. 20%, *Rosa canina* L. 15%. Herbaceous layer: *Hedera helix* L. 30%, *Helleborus* Tourn. 20%, *Cyclamen* spp. 20%, *Viola* spp. 20%. Parent material: Calcareous landslide; Parent rock: whitish micritic limestone. **Soil** (Soil Survey Staff, 2014): Humic Lithic Eutrudept										
OLn	3-1	1-3	-	-	-	-	-	-	-	-
OLv+OH	1-0		A, W	-	-	-	-	-	-	-
A	0-2	2-3	C, B	5 YR 3/2	3 vf, f, m, sbk	fr	Clay loam	3 vf, f	-	Interrupted horizon
Bw1	2-9	4-6	C, W	5 YR 3/4	3 vf, f, m, sbk	fr	Clay loam	3 vf, f; 2 m	20	Presence of mycelium
Bw2	9-17	5-9	C, W	5 YR 3/4	3 vf, f, m, sbk	fr	Clay loam	3 vf, f; 2 m	40	-
BC	17-26+	-	-	-	-	-	-	-	65	-
Plot L26c/Profile 2 (Gauss Boaga Rome 40 4794678 N, 2366639 E) Slope 35%; Exposure NO. Altitude: 630-785 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Turkey oak productive coppice (47 y). Presence of a charcoal kiln (3). Emerging rock: 5%. Soil cover: 90%. Vegetation. Trees: *Quercus cerris* L. 90%, *Ostrya carpinifolia* Scop. 40%, *Quercus pubescens* Willd. 30%, *Fraxinus ornus* L. 15%, *Sorbus aria* L. 15%. Bushes: *Juniperus communis* L. 40%, *Cornus mas* L.25%, *Rubus ulmifolius* L. 20%, *Rosa canina* L. 15%. Herbaceous layer: *Hedera helix* L. 30%, *Helleborus* Tourn. 20%, *Cyclamen* spp. 20%, *Viola* spp. 20%. Parent material: Calcareous landslide; Parent rock: whitish micritic limestone. **Soil** (Soil Survey Staff, 2014): Humic Lithic Eutrudept										
OLn	5-2	4-5	-	-	-	-	-	-	-	-
OLv+OH	2-0		C, W	-	3 gr	-	-	-	-	-

A	0-3	2-3	C, W	10 YR 3/2	3 vf, f, m, sbk	fr	Clay loam	3 vf, f	-	-
Bw	3-14	10-18	C, W	10 YR 3/4	3 vf, f, m, sbk	fr	Clay loam	3 vf, f; 2 m; 1 c, vc	30	Fragmented rock, secondary carbonates
CB	14-27+	-	-	7.5 YR 4/2	-	-	Clay loam	3 vf, f; 1 m	75	Fragmented rock

Plot L30b/Profile 1 (Gauss Boaga Rome 40 4794611 N, 2366741 E) Slope: 30%. Exposure: N. Altitude: 670-720 m a.s.l.– Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Turkey oak productive coppice (3-5 y). Emerging rock: 10%. Soil cover: 60-70%. Vegetation. Trees: *Quercus cerris* L. 60%, *Ostrya carpinifolia* Scop. 30%, *Acer opalus* Mill., *Fagus sylvatica* L., *Fraxinus ornus* L., *Prunus avium* L., *Sorbus domestica* L. Bushes: *Corylus avellana* L. 30%, *Cornus mas* L. 20%, *Coronilla aemerus* L. 5%, *Cytisus scoparius* L. 5%, *Rosa canina* L. 20%, *Rubus ulmifolius* L. 20%. Herbaceous layer: *Poa* spp. 30%, *Cyclamen* spp. 20%, *Hedera helix* L. 20%, *Helleborus* Tourn. 20%, *Daphne laureola* L. 5%, *Mentha* spp. 5%. Parent material: Calcareous landslide; Parent rock: whitish micritic limestone. **Soil** (Soil Survey Staff, 2014): Humic Lithic Eutrudept

OLn+OLv	1-0	0.5-2	A, S	5 YR 2/2	-	-	-	2 vf	< 2	
A	0-7	6.5-9	C, W	5 YR 3/2	3 vf, f, m, sbk	fr	Clay loam	3 vf, f; 1 m	2	
AB	7-14	6-10	G, W	5 YR 3/2	3 vf, f, m, sbk	fr	Clay loam	3 vf, f; 2 m	15	
Bw	14-35+	-	-	5 YR 3/3	3 vf, f, m, sbk	fr	Clay loam	3 vf, f; 2 m	40	Stone line

Plot L30b/Profile 2 (Gauss Boaga Rome 40 4794611 N, 2366748 E) Slope: 30%. Exposure: N. Altitude: 670-720 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Turkey oak productive coppice (3-5 y). Emerging rock: 10%. Soil cover: 60-70%. Vegetation. Trees: *Quercus cerris* L. 60%, *Ostrya carpinifolia* Scop. 30%, *Acer opalus* Mill., *Fagus sylvatica* L., *Fraxinus ornus* L., *Prunus avium* L., *Sorbus domestica* L. Bushes: *Corylus avellana* L. 30%, *Cornus mas* L. 20%, *Coronilla aemerus* L. 5%, *Cytisus scoparius* L. 5%, *Rosa canina* L. 20%, *Rubus ulmifolius* L. 20%. Herbaceous layer: *Poa* spp. 30%, *Cyclamen* spp. 20%, *Hedera helix* L. 20%, *Helleborus* Tourn. 20%, *Daphne laureola* L. 5%, *Mentha* spp. 5%. Parent material: Calcareous landslide; Parent rock: whitish micritic limestone. **Soil** (Soil Survey Staff, 2014): Humic Lithic Eutrudept

OLn	1.5-1	0.5	-	-	-	-	-	-	-	-
OLv+OH	1-0	0.5-3	V, W	10 YR 2/2	3 gr	-	-	3 vf, f	2	-
A	0-6	5-10	A, W	10 YR 3/2	3 vf, f, sbk	fr, ms	Clay loam	3 vf, f	2	-
Bw	6-29	18-22	C, W	10 YR 3/3	3 vf, f, sbk	fr, ms	Clay loam	3 vf, f; 1 m	50	Stone line
Bw$_b$	29-40+	-	-	10 YR 3/3	3 vf, f, sbk	fr, ms	Clay loam	3 vf, f; 1 m	40	Fragmented rock

Plot T2d/Profile 1 (Gauss Boaga Rome 40 4798441 N, 2363270 E) Slope: 40%. Expousure: N. Altitude: 1000-1140 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Beech coppice in conversion to high stand (50y). Presence of a charcoal kiln (2). Emerging rock: 2%. Soil cover: 100%. Vegetation. Trees: *Fagus sylvatica* L., *Sorbus aria* L. Bushes: *Crataegus monogyna* Jacq., *Prunus spinosa* L., *Rosa canina* L., *Rubus ulmifolius* L. Herbaceous layer: 60%, *Cyclamen* L., *Daphne* L. Parent material: Calcareous landslide; Parent rock: Red scale limestone. **Soil** (Soil Survey Staff, 2014): Humic Lithic Eutrudept

OLn	7-3	5-7	C,W	-	-	-	-	-	-	Mycelium
OLv+OH	3-0		A, S	-	-	-	-	-	-	-
A	0-4	2-3	C, S	10 YR 3/2	3 vf, f, m, sbk	vfr	Sandy loam	3 vf, f	5	Mycelium
Bw1	4-23	19-22	G, W	10 YR 4/3	2 vf, f, sbk	vfr, br	Sandy loam	3 vf, f; 2 m	30	Charcoal fragments
Bw2	23-48	23-27	C, W	10 YR 5/3	2 vf, f, m, sbk	vfr, br	Sandy loam	3 vf, f; 1 m	60	-
Bw3	48-54+	-	-	10 YR 5/4	2 vf, f, sbk	vfr, br	Sandy loam	1 vf, f	60	-

Plot T2d/Profile 2 (Gauss Boaga Rome 40 4798441 N, 2363279 E) Slope: 40%. Expousure: N. Altitude: 1000-1140 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Beech coppice in conversion to high stand (50y). Presence of a charcoal kiln (2). Emerging rock: 2%. Soil cover: 100%. Vegetation. Trees: *Fagus sylvatica* L., *Sorbus aria* L. Bushes: *Crataegus monogyna* Jacq., *Prunus spinosa* L., *Rosa canina* L., *Rubus ulmifolius* L. Herbaceous layer: 60%, *Cyclamen* L., *Daphne* L. Parent material: Calcareous landslide; Parent rock: Red scale limestone. **Soil** (Soil Survey Staff, 2014): Humic Lithic Eutrudept

OLn	4-2	4-8	-	-	-	-	-	-	-	-
OLv+OH	2-0		A, W	-	-	-	-	-	-	-
Bw1	0-8	5-8	C, W	10 YR 4/2	3 vf, f, sbk	vfr, br	Sandy loam	3 vf, f	15	-
Bw2	8-16	4-8	G, W	10 YR 4/3	2 vf, f, sbk	vfr, br	Sandy loam	3 vf, f; 2 m	30	-
Bw3	16-26	10-12	C, W	10 YR 5/6	2 vf, f, sbk	vfr, br	Sandy loam	3 vf, f; 2 m; 1 c	40	-
Bw4	26-42	15-20	C, W	10 YR 5/6	2 vf, f, sbk	vfr, br	Sandy loam	2 vf, f	60	-
BC	42-51+	-	-	10 YR 6/3	-	-	Sandy loam	1 vf, f	70	-

Plot T12c/Profile 1 (Gauss Boaga Rome 40 4798441 N, 2363275 E) Slope: 55%. Exposure: N. Altitude: 735-800 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Mixed oak stand managed as productive coppice (25 y). Emerging rock: 10%. Soil cover: 60%. Vegetation. Trees: *Quercus cerris* L. 60%, *Quercus pubescens* Willd. 20%, *Fraxinus ornus* L. 10%, *Ostrya carpinifolia* Scop. 10%, *Acer opalus* Mill., *Acer campestre* L. Bushes: *Rubus* L. 60%, *Lonicera caprifolium* L. 30%, *Prunus spinosa* L. 10%, *Crataegus monogyna* Jacq. Herbaceous layer: *Poa* spp, *Hedera helix* L.; Parent material: Calcareous landslide; Parent rock: Massive limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	11-4	7-11	-	-	-	-	-	-	-	-
OLv+OH	4-0		A, W	-	-	-	-	-	2	Mycelium
Bw1	0-10	8-11	C, W	5 YR 4/2	2 vf, f, sbk	fr	Clay loam	3 vf, f; 1 m, c	40	-
Bw2	10-18	5-7	C, W	5 YR 3/4	2 vf, f, sbk	fr	Clay loam	3 vf, f; 1 m, c	45	-
C	18-27+	-	-	-	-	fr	Clay loam	2 vf, f; 1 c, vc	-	-

Plot T12c/Profile 2 (Gauss Boaga Rome 40 4798441 N, 2363275 E) Slope: 55%. Exposure: N. Altitude: 735-800 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Mixed oak stand managed as productive coppice (25 y). Emerging rock: 10%. Soil cover: 60%. Vegetation. Trees: *Quercus cerris* L. 60%, *Quercus pubescens* Willd. 20%, *Fraxinus ornus* L. 10%, *Ostrya carpinifolia* Scop. 10%, *Acer opalus* Mill., *Acer campestre* L. Bushes: *Rubus* L. 60%, *Lonicera caprifolium* L. 30%, *Prunus spinosa* L. 10%, *Crataegus monogyna* Jacq. Herbaceous layer: *Poa* spp, *Hedera helix* L.; Parent material: Calcareous landslide; Parent rock: Massive limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	8-2.5	5-9	-	-	-	-	-	-	-	-
OLv+OH	2.5-0		C, W	-	-	-	-	-	-	-
A	0-3	2-3	C, W	5 YR 2/2	2 vf, f, m, sbk	fr	Clay loam	3 vf, f	20	Mycelium
Bw	3-12	10-12	C, W	5 YR 3/4	3 vf, f, sbk	fr	Clay loam	3 vf, f; 1 m	45	Mycelium
C	12-33+	-	-	-	-	fr	Clay loam	-	-	-

Plot T12e/Profile 1 (Gauss Boaga Rome 40 4797915 N, 2365757 E). Slope: 20-30%. Exposure: N-NE. Altitude: 780-820 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Turkey oak stand managed as productive coppice (20y). Emerging rock: -. Soil cover: 90%. Vegetation. Trees: *Ostrya carpinifolia* Scop. 55%, *Quercus cerris* L. 40%, *Acer campestre* L. 5%, *Fraxinus ornus* L., *Acer opalus* Mill. Bushes: *Crataegus monogyna* Jacq., *Juniperus oxycedrus* L., *Cytisus scoparius* L., *Lonicera caprifolium* L., *Rosa canina* L., *Rubus ulmifolius* L. Herbaceous layer: *Poa* spp, *Daphne laureola* L., *Hedera helix* L., *Helleborus* spp., *Viola* spp. Parent material: Calcareous landslide; Parent rock: whitish micritic limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn+OLv	3-0	1-3	C, W	-	-	-	-	-	-	-
A	0-5	2-5	C, W	10 YR 2/2	3 vf, f, gr	fr	Clay loam	2 vf	-	-
Bw1	5-10	3-6	C, W	10 YR 3/2	3 vf, f, m, sbk	fr	Clay loam	1 vf, f	30	Mesofauna activity
Bw2	10-20	7-10	C, W	10 YR 4/2	3 vf, f, m, sbk	fr	Clay loam	2 f, m; 1 c	50	-
BC	20-30	6-10	C, W	10 YR 4/3	1 vf, f, m, sbk	fr	Clay loam	3 vf, f, m	70	-
C/R	30-36+	-	-	-	-	-	-	-	-	-

Plot T12e/Profile 2 (Gauss Boaga Rome 40 4797915 N, 2365770 E). Slope: 20-30%. Exposure: N-NE. Altitude: 780-820 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Turkey oak stand managed as productive coppice (20y). Emerging rock: -. Soil cover: 90%. Vegetation. Trees: *Ostrya carpinifolia*

Scop. 55%, *Quercus cerris* L. 40%, *Acer campestre* L. 5%, *Fraxinus ornus* L., *Acer opalus* Mill. Bushes: *Crataegus monogyna* Jacq., *Juniperus oxycedrus* L., *Cytisus scoparius* L., *Lonicera caprifolium* L., *Rosa canina* L., *Rubus ulmifolius* L. Herbaceous layer: *Poa* spp, *Daphne laureola* L., *Hedera helix* L., *Helleborus* spp., *Viola* spp. Parent material: Calcareous landslide; Parent rock: whitish micritic limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	3-1	3	-	-	-	-	-	-	-	-
OLv+OH	1-0		C, W	-	-	-	-	-	-	-
A	0-2	2	C, W	10 YR 2/1	3 f, sbk	fr	Clay loam	-	2	-
AB	2-4	2.5	C, W	10 YR 3/2	3 f, m, sbk	fr	Clay loam	1 f	5	-
Bw	4-15	10	C, W	10 YR 3/2	2 f, sbk	fr	Clay loam	2 f; 1 c	50	Mesofauna activity
BC	15-19	5.5	C, W	-	1 vf, f, m sbk	fr	Clay loam	1 f; 2 m; 1 c	75	-
C/R	19-32+	-	-	-	-	-	-	-	-	-

Plot T12f/Profile 1 (Gauss Boaga Rome 40 4797985 N, 2365752 E) Slope: 30-40%. Exposure: N. Altitude: 745-810 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Turkey oak high stand (60 y). Emerging rock: -. Soil cover: 90%. Vegetation. Trees: *Quercus cerris* L. 65%, *Acer opalus* Mill. 20%, *Ostrya carpinifolia* Scop. 10%, *Acer campestre* L., *Fraxinus ornus* L., *Prunus avium* L., *Quercus pubescens* Willd. Bushes: *Crataegus monogyna* Jacq. 50%, *Rubus* L. 40%, *Cornus mas* L., *Euonymus europaeus* L., *Rosa* L, novellame di *Acer opalus* Mill., *Acer campestre* L., *Fagus sylvatica* L. 10%. Herbaceous layer: *Poa* spp., *Daphne laureola* L., *Hedera helix* L., *Primula* spp. Parent material: Calcareous landslide; Parent rock: whitish micritic limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn+OLv+OH	2-1	1	C, W	-	-	-	-	-	-	-
Oa	1-0	1-2	C, W	-	-	-	-	-	-	-
AB	0-3	3-5	C, W	7.5 YR 3/2	3 vf, f, m, abk, sbk	fr	Clay loam	1 vf; 2 f; 1 m	1-5	Mesofauna activity
Bw1	3-21	18-20	C, W	7.5 YR 3/2	2-3 vf, f, m, abk, sbk	fr	Clay loam	1 vf, f; 2 m	60	-
Bw2	21-35+	-	-	7.5 YR 3/2	2-3 vf, f, m abk, sbk	fr	Clay loam	2 f; 1 m	40	Mesofauna activity

Plot T12f/Profile 2 (Gauss Boaga Rome 40 4797985 N, 2365762 E) Slope: 30-40%. Exposure: N. Altitude: 745-810 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Turkey oak high stand (60 y). Emerging rock: -. Soil cover: 90%. Vegetation. Trees: *Quercus cerris* L. 65%, *Acer opalus* Mill. 20%, *Ostrya carpinifolia* Scop. 10%, *Acer campestre* L., *Fraxinus ornus* L., *Prunus avium* L., *Quercus pubescens* Willd. Bushes: *Crataegus monogyna* Jacq. 50%, *Rubus* L. 40%, *Cornus mas* L., *Euonymus europaeus* L., *Rosa* L, novellame di *Acer opalus* Mill., *Acer campestre* L., *Fagus sylvatica* L. 10%. Herbaceous layer: *Poa* spp., *Daphne laureola* L., *Hedera helix* L., *Primula* spp. Parent material: Calcareous landslide; Parent rock: whitish micritic limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	3-1	2	C, W	-	-	-	-	-	-	-
OLv+OH	1-0	1	C, W	-	-	-	-	-	-	-
A	0-3	3-4	C, W	7.5 YR 2/2	3 f, m, sbk	fr	Clay loam	2 f	2-5	Mesofauna activity
Bw1	3-8	4.5-5	C, W	10 YR 3/3	3 vf, f, m, abk, sbk	fr	Clay loam	2 vf, f	25	-
Bw2	8-20	12-13.5	C, W	10 YR 3/3	2 vf, f, abk	fr	Clay loam	2 f, m; 1 c	60	-
BC	30-36+	-	-	10 YR 3/4	2 vf, f, abk	fi	Clay loam	2 f, m	80	Limestone with flint lenses

Plot T12h/Profile 1. (Gauss Boaga Rome 40 4797985 N, 2365759 E) Slope: 35%. Exposure: N. Altitude: 705-730 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Mixed oak stand in conversion to high forest. Emerging rock: 30%. Soil cover: 50%. Vegetation. Trees: *Quercus pubescens* Willd. 40%, *Fraxinus ornus* L. 20%, *Ostrya carpinifolia* Scop. 20%, *Acer campestre* L. 10%, *Acer opalus* Mill. 10%, *Prunus avium* L., *Sorbus aria* L., *Sorbus domestica* L. Bushes: *Cornus mas* L. 30%, *Juniperus communis* L. 30%, *Genista* spp. 20%, *Euonymus europaeus* L. 10%, *Prunus spinosa* L. 10%, *Lonicera* spp. Herbaceous layer: *Poa* spp., *Daphne laureola* L., *Hedera helix* L. Parent material: Calcareous landslide; Parent rock: Massive limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	6-3		-	-	-	-	-	-	-	-
OLv+OH	3-0	2-6	A, W	-	-	-	-	3 vf, f; 1 vc	-	-
A	0-6	4-12	C, I	5 YR 3/2	3 vf, f, sbk	fr	Clay	3 vf, f; 2 m; 1 vc	20	-

Bw1	6-21	4-15	C, W	5 YR 4/2	3 vf, f, m, sbk	fr	Clay	2 vf, f; 1 m, vc	35	-
Bw2	21-30	9-10	C, W	5 YR 4/4	3 vf, f, sbk	fr	Clay	2 vf, f; 1 c, vc	45	-
BC	30-34+	-	-	-	-	-	Clay	-	-	-

Plot T12h/Profile 2. (Gauss Boaga Rome 40 4797985 N, 2365759 E) Slope: 35%. Exposure: N. Altitude: 705-730 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Mixed oak stand in conversion to high forest. Emerging rock: 30%. Soil cover: 50%. Vegetation. Trees: *Quercus pubescens* Willd. 40%, *Fraxinus ornus* L. 20%, *Ostrya carpinifolia* Scop. 20%, *Acer campestre* L. 10%, *Acer opalus* Mill. 10%, *Prunus avium* L., *Sorbus aria* L., *Sorbus domestica* L. Bushes: *Cornus mas* L. 30%, *Juniperus communis* L. 30%, *Genista* spp. 20%, *Euonymus europaeus* L. 10%, *Prunus spinosa* L. 10%, *Lonicera* spp. Herbaceous layer: *Poa* spp., *Daphne laureola* L., *Hedera helix* L. Parent material: Calcareous landslide; Parent rock: Massive limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	8-3	7-9	-	-	-	-	-	3 vf, f	2	
OLv+OH	3-0		C, W	-	-	-	-	-		
A	0-8	6-9.5	C, W	7.5 YR 3/2	3 vf, f, sbk	fr	Clay	3 vf, f; 2 m,	25	-
Bw1	8-26	8-17	C, W	7.5 YR 5/4	3 vf, f, m, sbk	fr	Clay	2 vf, f; 1 m	40	-
Bw2	26-31	5-6	C, W	7.5 YR 4/4	3 vf, f, sbk	fr	Clay	2 vf, f	60	-
BC	31-36+	-	-	7.5 YR 4/4	2 vf, f, sbk	fr	Clay	1 vf, f	-	-

Plot T13b/Profile 1 (Gauss Boaga Rome 40 4797826 N, 2365533 E) Slope: 40%. Exposure: NO. Altitude: 800-870 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Mixed oak stand managed as productive coppice. Emerging rock: -. Soil cover: 80%. Vegetation. Trees: *Quercus cerris* L. 40%, *Quercus pubescens* Willd. 30%, *Ostrya carpinifolia* Scop. 20%, *Acer opalus* Mill. 5%, *Fraxinus ornus* L. 5%, *Fagus sylvatica* L. Copertura arbustiva: *Coronilla* spp. (20%), *Juniperus oxycedrus* L., *Lonicera caprifolium* L., *Rosa canina* L, 80%. Herbaceous layer: *Poa* spp. (70%), *Daphne laureola* L. (10%), *Hedera helix* L., *Hepatica nobilis* Schreb., *Viola* spp.; Parent material: Calcareous landslide; Parent rock: Massive limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	8-2	4-7	C, W	-	-	-	-	-	-	-
OLv+OH	2-0	1-3	C, W	-	-	-	-	-	-	

Bw1	0-4	3-5	C, W	7.5 YR 4/6	3 vf, f, m, sbk	sh, br	Clay	3 vf, f; 1 m	10	Dry
Bw2	4-23	18-20	C, W	7.5 YR 3/4	3 vf, f, m, sbk	mp	Clay	1 vf, f; 1 m, c	50	-
Bw3	23-37+	-	-	7.5 YR 4/6	3 vf, f, m, sbk	mp	Clay	2 f, c; 1 vc	70	-

Plot T13b/Profile 2 (Gauss Boaga Rome 40 4797826 N, 2365543 E) Slope: 40%. Exposure: NO. Altitude: 800-870 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Mixed oak stand managed as productive coppice. Emerging rock: -. Soil cover: 80%. Vegetation. Trees: *Quercus cerris* L. 40%, *Quercus pubescens* Willd. 30%, *Ostrya carpinifolia* Scop. 20%, *Acer opalus* Mill. 5%, *Fraxinus ornus* L. 5%, *Fagus sylvatica* L. Copertura arbustiva: *Coronilla* spp. (20%), *Juniperus oxycedrus* L., *Lonicera caprifolium* L., *Rosa canina* L, 80%. Herbaceous layer: *Poa* spp. (70%), *Daphne laureola* L. (10%), *Hedera helix* L., *Hepatica nobilis* Schreb., *Viola* spp.; Parent material: Calcareous landslide; Parent rock: Massive limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn+OLv+OH	3-0	3	A, W	-	-	-	-	3 vf; 2 f	2	-
Bw	0-8	5-8	C, W	7.5 YR 4/6	3 vf, f, sbk	mp	Clay	2 vf, f; 1 m	10	-
$Bw1_b$	8-12	4-7	C, W	7.5 YR 4/6	3 vf, f, sbk	mp	Clay	2 vf, f, vc; 1 m	20	-
$Bw2_b$	12-24	12-14.5	C, W	7.5 YR 4/6	3 vf, f, sbk	mp	Clay	2 vf, vc; 1 m	50	-
BC_b	24-38+	-	-	7.5 YR 4/6	3 vf, f, sbk	mp	Clay	2 vf, f; 1 m, vc	70	-

Plot T16d/Profile 1 (Gauss Boaga Rome 40 4797635 N, 2364411 E) Slope: 10-15%. Exposure: N. Altitude: 830-860 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Mixed oak stand in conversion to high forest (60 y). Emerging rock: 2%. Soil cover: 85%. Vegetation. Trees: *Quercus cerris* L. 40%, *Acer opalus* Mill. 30%, *Ostrya carpinifolia* Scop. 20%, *Acer campestre* L. 5%, *Carpinus betulus* L., *Fraxinus ornus* L., *Prunus avium* L., *Quercus pubescens* Willd. Bushes: *Corylus avellana* L. 60%, *Cornus mas* L. 20%, *Crataegus monogyna* Jacq., *Prunus spinosa* L., *Rosa canina* L., *Rubus ulmifolius* L. Herbaceous layer: *Poa* spp., *Hedera helix* L., *Viola* spp.; Parent material: Calcareous landslide; Parent rock: Massive limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	7-3	6-9	-	-	-	-	-	-	-	-
OLv	3-0		A, S	-	-	-	-	-	-	-

Bw1	0-7	6-9	C, W	7.5 YR 4/2	3 vf, f, m, sbk	fr	Clay loam	3 vf, f; 1 m	5-10	-
Bw2	7-37	26-30	C, W	7.5 YR 4/2	3 vf, f, m, sbk	fr	Clay loam	3 vf, f; 2 m; 1 c	50	-
Bw3	37-48+	-	-	7.5 YR 4/4	3 vf, f, m, sbk	fr	Clay loam	2 vf, f	10	Charcoal fragments
Plot T16d/Profile 2 (Gauss Boaga Rome 40 4797635 N, 2364415 E) Slope: 10-15%. Exposure: N. Altitude: 830-860 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Mixed oak stand in conversion to high forest (60 y). Emerging rock: 2%. Soil cover: 85%. Vegetation. Trees: *Quercus cerris* L. 40%, *Acer opalus* Mill. 30%, *Ostrya carpinifolia* Scop. 20%, *Acer campestre* L. 5%, *Carpinus betulus* L., *Fraxinus ornus* L., *Prunus avium* L., *Quercus pubescens* Willd. Bushes: *Corylus avellana* L. 60%, *Cornus mas* L. 20%, *Crataegus monogyna* Jacq., *Prunus spinosa* L., *Rosa canina* L., *Rubus ulmifolius* L. Herbaceous layer: *Poa* spp., *Hedera helix* L., *Viola* spp.; Parent material: Calcareous landslide; Parent rock: Massive limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept										
OLn	4-2	2-4	-	-	-	-	-	-	-	-
OLv+OH	2-0		A, S	-	-	-	-	-	-	-
Bw1	0-7	7-9	C, W	5 YR 4/2	3 vf, f, m, c, sbk	fr	Clay loam	3 vf, f; 2 m	5-10	-
Bw2	7-32	20-25	C, W	5 YR 4/2	3 vf, f, m, sbk	fr	Clay loam	3 vf, f, m	45	-
Bw3	32-44+	-	-	5 YR 3/2	3 vf, f, m, sbk	fr	Clay loam	3 vf, f	10	Charcoal fragments
Plot T17b/Profile 1. (Gauss Boaga Rome 40 4797165 N, 2364101 E) Slope: 5-10%. Exposure: N. Altitude: 1160-1180 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Old beech coppice (70 y). Emerging rock: 5-10%. Soil cover: 80%. Vegetation. Trees: *Fagus sylvatica* L. 95%, *Fraxinus ornus* L. 5%, *Ostrya carpinifolia* Scop., *Sorbus aria* L. Bushes: *Crataegus monogyna* Jacq., *Euonymus europaeus* L. Herbaceous layer: *Cyclamen* spp., *Daphne laureola* L.; Parent material: Calcareous landslide; Parent rock: Red scale limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept										
OLn	12-5	10-14	-	-	-	-	-	-	-	-
OLv+OH	5-0		C, W	-	-	-	-	-	-	Mycelium

A	0-8	8-9	C, S	7.5 YR 3/2	3 vf, f, m, c, sbk	fi, br	Clay loam	3 vf, f; 1 m, c	2	-
Bw	8-25	13-21	A, W	10 YR 3/4	3 vf, f, sbk	fr	Clay loam	3 vf, f; 2 m; 1 c, vc	40	Secondary carbonates
CB	25-48+	-	-	10 YR 7/3	-	-	-	-	70	Crushed rock

Plot T17b/Profile 2. (Gauss Boaga Rome 40 4797165 N, 2364107 E) Slope: 5-10%. Exposure: N. Altitude: 1160-1180 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Old beech coppice (70 y). Emerging rock: 5-10%. Soil cover: 80%. Vegetation. Trees: *Fagus sylvatica* L. 95%, *Fraxinus ornus* L. 5%, *Ostrya carpinifolia* Scop., *Sorbus aria* L. Bushes: *Crataegus monogyna* Jacq., *Euonymus europaeus* L. Herbaceous layer: *Cyclamen* spp., *Daphne laureola* L.; Parent material: Calcareous landslide; Parent rock: Red scale limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	7-5	4-11	-	-	-	-	-	-	-	-
OLv+OH	5-0		C, W	-	-	-	-	-	2	Mycelium
A	0-9	9-11	C, W	5 YR 2/2	3 vf, f, sbk	fr	Clay loam	3 vf, f; 2 m, c; 1 vc	10	-
Bw	9-29	19-22	C, W	5 YR 4/2	3 vf, f, m, sbk	fi	Clay loam	3 vf, f; 2 m; 1 vc	40	Secondary carbonates
BC	29-44+	-	-	5 YR 4/4	3 vf, f, sbk	fi, br	Clay loam	2 vf, f	50	Crushed rock

Plot T23c/Profile 1. (Gauss Boaga Rome 40 4797742 N, 2364649 E) Slope: 30-40%. Exposure: NO. Altitude: 810-870 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Hornbeam and manna ash productive coppice (7 y). Emerging rock: 10%. Soil cover: 80%. Vegetation. Trees: *Ostrya carpinifolia* Scop. 80%, *Fagus sylvatica* L. 20%, *Fraxinus ornus* L. 10%, *Quercus cerris* L. 10%, *Quercus pubescens* Willd. 10%, *Acer campestre* L., *Acer opalus* Mill. Bushes: *Clematis vitalba* L., *Crataegus monogyna* Jacq., *Coronilla aemerus* L., *Corylus avellana* L., *Rosa canina* L., *Rubus ulmifolius* L. Herbaceous layer: 30%, *Poa* spp., *Cyclamen* spp., *Daphne laureola* L., *Fragaria vesca* L., *Hedera helix* L., *Lathyrus venetus* Mill., *Sanicula europaea* L., *Viola* spp.; Parent material: Calcareous landslide; Parent rock: Massive limestone.

Soil (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn+OLv+OH	5-0	3-6	C, W	-	-	-	-	-	-	-
AB	0-3	2-3	C, W	10 YR 3/2	3 vf, f, m, sbk	fr	Clay loam	3 vf, f; 1 m	< 5	-
Bw1	3-8	4-6	C, W	10 YR 3/3	3 vf, f, m, c, sbk	fr	Clay loam	3 vf, f	5	-
Bw2	8-22	10-15	C, W	10 YR 3/3	3 f, m, c, sbk	fr	Clay loam	3 vf, f; 2 m	5	Popping aggregates
Bw3	22-33	8-13	C, W	10 YR 3/4	2 f, m, c, sbk	fr	Clay loam	1 vf, f	70	Popping aggregates
Bw4	33-48+	-	-	10 YR 3/6	2 vf, f, m, sbk	fr	Clay loam	1 f	70	Popping aggregates

Plot T23c/Profile 2. (Gauss Boaga Rome 40 4797742 N, 2364653 E) Slope: 30-40%. Exposure: NO. Altitude: 810-870 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Hornbeam and manna ash productive coppice (7 y). Emerging rock: 10%. Soil cover: 80%. Vegetation. Trees: *Ostrya carpinifolia* Scop. 80%, *Fagus sylvatica* L. 20%, *Fraxinus ornus* L. 10%, *Quercus cerris* L. 10%, *Quercus pubescens* Willd. 10%, *Acer campestre* L., *Acer opalus* Mill. Bushes: *Clematis vitalba* L., *Crataegus monogyna* Jacq., *Coronilla aemerus* L., *Corylus avellana* L., *Rosa canina* L., *Rubus ulmifolius* L. Herbaceous layer: 30%, *Poa* spp., *Cyclamen* spp., *Daphne laureola* L., *Fragaria vesca* L., *Hedera helix* L., *Lathyrus venetus* Mill., *Sanicula europaea* L., *Viola* spp.; Parent material: Calcareous landslide; Parent rock: Massive limestone.
Soil (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn+OLv+OH	2-0	2	C, W	-	-	-	-	3 vf; 2 f	2	-
A	0-2	1.5-2	C, W	10 YR 3/3	3 f, sbk	fr	Clay loam	2 vf, f	5	-
AB	2-6	4.5-5	C, S	10 YR 4/4	3 f, m, sbk	fr	Clay loam	2 vf, f; 1 c	5	-
Bw	6-13	6.5-8	C, W	10 YR 4/4	3 f, m, sbk	fr	Clay loam	2 vf, f; 1 c	15	Stone line
AB_b	13-18	5-6	C, W	7.5 YR 4/4	3 f, m, sbk	fr	Clay loam	2 vf, f;	25	-

								1 m		
$Bw1_b$	18-27	8.5-9	C, W	7.5 YR 4/4	3 f, m, sbk	fr	Clay loam	2 vf, f; 1 m	10	-
$Bw2_b$	27-33	6-10	C, W	10 YR 4/4	3 vf, sbk	fr	Clay loam	2 vf, f; 1 m	10	-
$Bw3_b$	33-48+	-	-	10 YR 5/4	3 vf, sbk	fr	Clay loam	2 vf, f; 1 m	40	-

Plot T23d/Profile 1 (Gauss Boaga Rome 40 4797523 N, 2364651 E) Slope: 50-60%. Exposure: NO. Altitude: 845-970 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Beech coppice (40 y). Emerging rock: 30%. Soil cover: 80%. Vegetation. Trees: *Fagus sylvatica* L. 50%, *Ostrya carpinifolia* Scop. 40%, *Acer opalus* Mill., *Fraxinus ornus* L., *Quercus cerris* L., *Quercus pubescens* Willd, *Sorbus aria* L. Bushes: -. Herbaceous layer: *Poa* spp., *Hedera helix* L., *Viola* spp., 10%.; Parent material: Calcareous landslide; Parent rock: Red scale limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	10-7	1-5	C, W	-	-	-	-	-	-	-
OLv+OH	7-0	4-7	C, W	-	-	-	-	-	-	Mycelium
A	0-3	2-3	C, W	10 YR 3/2	3 vf, gr; 3 vf, f, m, sbk	fr	Clay loam	3 vf, f	-	Popping aggregates
AB	3-6	3-5	C, W	10 YR 3/3	3 vf, f, m, sbk	fr	Clay loam	3 vf, f	50	Stone line
AB_b	11-14	1-3	C, W	10 YR 3/3	3 vf, f, m, sbk	fr	Clay loam	2 vf, f, m; 1 c	10	-
$Bw1_b$	14-20	4-7	C, W	10 YR 3/4	3 vf, f, m, sbk	fr, br	Clay loam	1 vf; 2 f, m	10	-
$Bw2_b$	20-29	4-9	C, W	10 YR 3/6	3 vf, f, m, sbk	fr	Clay loam	1 vf; 2 f, m	30	Popping aggregates
$Bw3_b$	29-49+	-	-	10 YR 3/6	3 vf, f, m, c, sbk	fr	Clay loam	1 vf, f, m	40	Popping aggregates

Plot T23d/Profile 2 (Gauss Boaga Rome 40 4797523 N, 2364656 E) Slope: 50-60%. Exposure: NO. Altitude: 845-970 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Beech coppice (40 y). Emerging rock: 30%. Soil cover: 80%. Vegetation. Trees: *Fagus sylvatica* L. 50%, *Ostrya carpinifolia* Scop. 40%, *Acer opalus* Mill., *Fraxinus ornus* L., *Quercus cerris* L., *Quercus pubescens* Willd, *Sorbus aria* L. Bushes: -. Herbaceous layer: *Poa* spp., *Hedera helix* L., *Viola* spp., 10%.;

Parent material: Calcareous landslide; Parent rock: Red scale limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept										
OLn	4-3	1	A, S	-	-	-	-	-	30	-
OLv+OH	3-0	3	C, S	-	3 gr	-	-	2 vf	5	-
A	0-2	2	C, S	7.5 YR 2/2	3 f, sbk	fr	Clay loam	3 vf, f; 1 c	5	-
AB	2-6	3.5-5	C, W	10 YR 4/2	3 vf, f, m, sbk, abk	fr	Clay loam	3 vf, f; 2 m	15	Stone line
Bw1b	6-11	6.5-9	C, S	10 YR 4/4	3 vf, f, sbk	mp	Clay loam	3 vf, f; 2 m	30	Stone line
Bw2b	11-23	11	C, S	10 YR 4/4	3 vf, f, sbk	mp	Clay loam	3 vf, f; 2 m; 1 c	40	-
Bw3b	23-36	13	C, W	10 YR 4/4	3 vf, f, sbk	mp	Clay loam	2 vf, f; 1 c	40	-
Bw4b	36-48+	-	-	10 YR 4/4	3 vf, sbk	mp	Clay loam	2 f, m; 1 c, vc	60	Mesofauna activity
Plot T33a/Profile 1 (Gauss Boaga Rome 40 4796154 N, 2364668 E) Slope: 70-80%. Exposure: N. Altitude: 1050-1105 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Beech high stand (80 y). Emerging rock: 20%. Soil cover: 95%. Vegetation. Trees: *Fagus sylvatica* L. 95%, *Acer opalus* Mill., *Ostrya carpinifolia* Scop. Bushes: *Ilex aquifolium* L., *Rubus ulmifolius* L. Herbaceous layer: *Poa* spp., *Cyclamen* spp., *Daphne laureola* L., *Hedera helix* L., *Hepatica nobilis* Schreb., *Lathyrus venetus* Mill., *Sanicula europaea* L., *Viola* spp.; Parent material: Calcareous landslide; Parent rock: Red scale limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept										
OLn	13-4	3-8	C, W	-	-	-	-	-	-	Mesofauna activity
OLv+OH	4-0	1-4	C, W	-	3 vf, f, gr	fr	-	3 vf	-	Mesofauna activity
AB	0-3	1-3	C, W	5 YR 3/3	3 vf, f, sbk	mp	Clay	3 vf; 2 f; 1 m	-	-
Bw1	3-7	3-7	C, W	5 YR 4/6	3 vf, f, m,	fr	Clay loam	3 vf, f;	25	Mesofauna

					sbk			1 m		activity
Bw2	7-25	8-18	C, W	5 YR 3/4	3 vf, f, m, sbk	fr	Clay	1 f, m, c; 2 vc	20	Mesofauna activity
Bw3	25-46+	-	-	2.5 YR 3/4	3 f, m, c, sbk	sp	Clay	2 f; 1 m	40	-

Plot T33a/Profile 2 (Gauss Boaga Rome 40 4796154 N, 2364672 E) Slope: 70-80%. Exposure: N. Altitude: 1050-1105 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Beech high stand (80 y). Emerging rock: 20%. Soil cover: 95%. Vegetation. Trees: *Fagus sylvatica* L. 95%, *Acer opalus* Mill., *Ostrya carpinifolia* Scop. Bushes: *Ilex aquifolium* L., *Rubus ulmifolius* L. Herbaceous layer: *Poa* spp., *Cyclamen* spp., *Daphne laureola* L., *Hedera helix* L., *Hepatica nobilis* Schreb., *Lathyrus venetus* Mill., *Sanicula europaea* L., *Viola* spp.; Parent material: Calcareous landslide; Parent rock: Red scale limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	2-1	1	-	-	-	-	-	-	-	-
OLv+OH	1-0	1	C, S	-	-	-	-	3 vf, f; 2 m; 1 c	5	-
A	0-4	4,5	C, W	5 YR 3/2	3 vf, f, m, sbk	fr	Clay	3 vf, f; 1 m, c	2-5	-
AB	4-7	3-4	C, W	5 YR 3/3	3 vf, f, m, abk	fi	Clay	2 vf, f; 1 m	70	-
Bw	7-27	20-23	C, W	5 YR 3/3	3 vf, f, m, c, vc, abk	fr	Clay	2 vf, f; 3 m; 1 c, vc	50	-
BC	27-46+	-	-	-	-	-	-	2 vf, f; 1 m, c	-	-

Plot T33b/Profile 1 (Gauss Boaga Rome 40 4796403 N, 2364751 E) Slope: 50%. Exposure: NO. Altitude: 965-1150 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Beech coppice in conversion to high stand (45 y). Emerging rock: 10%. Soil cover: 95%. Vegetation. Trees: *Fagus sylvatica* L. 98%, 2% *Acer opalus* Mill., *Ostrya carpinifolia* Scop., *Quercus pubescens* Willd., *Sorbus aria* L. Bushes: *Lonicera caprifolium* L., *Rubus ulmifolius* L. Herbaceous layer: *Poa* spp., *Cardamine kitaibelii* Bech., *Cyclamen* spp., *Daphne laureola* L., *Euphorbia dulcis* L., *Hedera helix* L., *Helleborus* spp., *Hepatica nobilis* Schreb., *Viola* spp.; Parent material: Calcareous landslide; Parent rock: Red scale limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	5-2	4-6	C, W	-	-	-	-	-	-	-
OLv+OH	2-0	1-2	C, W	-	3 vf, gr	fr	-	3 vf, f	-	-
A	0-4	3-5	C, W	7.5 YR 3/4	3 vf, gr; 3 vf, f, m, sbk	fr	Clay loam	3 vf, f; 2 m	-	-
AB	4-7	3-5	C, W	7.5 YR 3/4	3 vf, f, m, sbk	fr	Clay loam	3 vf, f, m; 1 c, vc	20	-
Bw1	7-13	6-9	C, W	7.5 YR 4/4	3 vf, f, m, sbk	fr	Clay loam	3 vf, f; 1 m	30	-
Bw2	13-33	15-20	C, W	7.5 YR 4/4	3 vf, f, m, sbk	fr	Clay loam	2 vf; 3 f, m; 1 c	50	Slightly popping aggregates
Bw3	33-44	10-12	C, W	7.5 YR 4/6	3 vf, f, m, sbk	fr	Clay loam	3 vf, f	60	-
CB	44-53+	-	-	7.5 YR 6/3	1 vf, sg; 1 f, sbk	fr	Clay loam	3 vf, f; 2 m	70	-

Plot T33b/Profile 2 (Gauss Boaga Rome 40 4796403 N, 2364756 E) Slope: 50%. Exposure: NO. Altitude: 965-1150 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Beech coppice in conversion to high stand (45 y). Emerging rock: 10%. Soil cover: 95%. Vegetation. Trees: *Fagus sylvatica* L. 98%, 2% *Acer opalus* Mill., *Ostrya carpinifolia* Scop., *Quercus pubescens* Willd., *Sorbus aria* L. Bushes: *Lonicera caprifolium* L., *Rubus ulmifolius* L. Herbaceous layer: *Poa* spp., *Cardamine kitaibelii* Bech., *Cyclamen* spp., *Daphne laureola* L., *Euphorbia dulcis* L., *Hedera helix* L., *Helleborus* spp., *Hepatica nobilis* Schreb., *Viola* spp.; Parent material: Calcareous landslide; Parent rock: Red scale limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

O	1-0	1	C, S	-	3 gr	-	-	-	5	-
A	0-2	2-3	C, W	5 YR 3/2	3 vf, f, sbk	mp	Clay loam	3 vf, f;	5	-

								1 m, c		
AB	2-7	5-7	C, W	5 YR 3/2	3 vf, f, sbk	mp	Clay loam	3 vf, f, 2 m	2-5	-
Bw1	7-19	10-12	C, W	5 YR 4/3	3 vf, f, abk	mp	Clay loam	3 vf, f; 2 m; 1 c	40	-
Bw2	19-41	15-23	C, W	5 YR 4/3	3 vf, abk	mp	Clay loam	3 vf, f; 1 m, c, vc	50	-
CB	41-53+	-	-	-	3 vf, sg	-	-	3 vf, f; 1 m, c, vc	70	-

Plot T35e/Profile 1 (Gauss Boaga Rome 40 4796441 N, 2365172 E). Slope: 20%. Exposure: N. Altitude: 1020-1075 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Beech coppice. Emerging rock: 5%. Soil cover: 95%. Vegetation. Trees: 70%, *Fagus sylvatica* L. 80%, *Ostrya carpinifolia* Scop. 10%, *Fraxinus ornus* L. 5%, *Quercus cerris* L. 5%, *Acer campestre* L. (sporadic). Bushes: 20%, *Cornus mas* L. 30%, *Corylus avellana* L. 30%, *Clematis vitalba* L. 20%, *Rubus* L. 10%. Herbaceous layer: 20%, *Cyclamen* L., *Daphne* L., *Hedera helix* L., *Mercurialis* L.; Parent material: Calcareous landslide; Parent rock: whitish micritic limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	10-5	7-10	-	-	-	-	-	-	-	-
OLv+OH	5-0		A, W	-	-	-	-	3 vf, f	2	-
AE	0-10	10-14	C, W	7.5 YR 4/2	3 vf, f, m, sbk, abk	fr, br	Clay loam	3 vf, f; 2 m, c	2	-
Bw	10-34	11-24	C, W	7.5 YR 3/2	3 vf, f, m sbk	fr	Clay loam	3 vf, f; 2 m, c, vc	60	-
BC	34-36+	-	-	7.5 YR 4/2	3 vf, f, sbk	fr	-	1 vf, f	70	Secondary carbonates, charcoal fragments

Plot T35e/Profile 2 (Gauss Boaga Rome 40 4796441 N, 2365187 E). Slope: 20%. Exposure: N. Altitude: 1020-1075 m a.s.l. – Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Beech coppice. Emerging rock: 5%. Soil cover: 95%. Vegetation. Trees: 70%, *Fagus sylvatica* L. 80%, *Ostrya carpinifolia* Scop. 10%, *Fraxinus ornus* L. 5%, *Quercus cerris* L. 5%, *Acer campestre* L. (sporadic). Bushes: 20%, *Cornus mas* L. 30%, *Corylus avellana* L. 30%, *Clematis vitalba* L. 20%, *Rubus* L. 10%. Herbaceous layer: 20%, *Cyclamen* L., *Daphne* L., *Hedera helix* L., *Mercurialis* L.; Parent material: Calcareous landslide; Parent rock: whitish micritic limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	4-2	3-5	-	-	-		-	-	-	-
OLv+OH	2-0		A, W	-	-		-	-	-	-
A	0-7	7-9	C, W	5 YR 3/2	3 vf, f sbk	fi	Clay loam	3 vf, f; 1 m, c, vc	5	-
Bw1	7-21	10-13	C, W	5 YR 3/2	3 vf, f, m sbk	fr	Clay loam	3 vf, f; 2 m; 1 c, vc	60	-
Bw2	21-36	8-15	C, W	5 YR 4/2	3 vf, f, m, sbk	fr	Clay loam	3 vf, f; 1 m, vc	70	Rock and charcoal fragments
BC	36-39+	-	-	5 YR 4/4	-	-	-	1 vf, f, vc -	75	-

Plot T38a/Profile 1 (Gauss Boaga Rome 40 4796839 N, 2365631 E). Slope: 20%. Exposure: N-NO. Altitude: 830-910 m a.s.l. - Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Turkey oak coppice. Emerging rock: 30%. Soil cover: <5%. Vegetation. Trees: 40%, *Quercus cerris* L. (95%), *Ostrya carpinifolia* Scop. (5%). Bushes: 60%, *Corylus avellana* L. 20%, *Rosa* L, *Rubus* L. 80%, *Acer opalus* Mill., *Fagus sylvatica* L., *Faxinus ornus* L., *Ostrya carpinifolia* Scop., *Quercus cerris* L., *Sorbus aria* (L.) Crantz. suckers; Herbaceous layer: 80%, *Poa spp.* 85%, *Pteridophyte*, spp. 10%, (5%) di *Acer opalus* Mill., *Fraxinus ornus* L., *Quercus cerris* L. seedlings; Parent material: Calcareous landslide; Parent rock: whitish micritic limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn+OLv+OH	4-0	2-5	C, W	-	-	-	-	3 vf	-	-
AB	0-3	3-5	C, W	7.5 YR 3/2	3 vf, f, m, sbk	fr, mp	Clay	3 vf, 2 f	20	-
Bw1	3-12	5-9	C, W	10 YR 4/3	3 vf, f, m, sbk	mp	Clay	1 vf, f, m	30	-

Bw2	12-25	10-13	C, W	7.5 YR 4/6	3 vf, f, m sbk	mp	Clay	1 vf, f, m	40	-
Bw3	25-41+	-	-	7.5 YR 4/4	3 vf, f, m, sbk	mp	Clay	1 vf, f, m	60	-

Plot T38a/Profile 2 (Gauss Boaga Rome 40 4796839 N 2365631 E). Slope: 20%. Exposure: N-NO. Altitude: 830-910 m a.s.l. - Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Turkey oak coppice. Emerging rock: 30%. Soil cover: <5%. Vegetation. Trees: 40%, *Quercus cerris* L. (95%), *Ostrya carpinifolia* Scop. (5%). Bushes: 60%, *Corylus avellana* L. 20%, *Rosa* L, *Rubus* L. 80%, *Acer opalus* Mill., *Fagus sylvatica* L., *Faxinus ornus* L., *Ostrya carpinifolia* Scop., *Quercus cerris* L., *Sorbus aria* (L.) Crantz. suckers; Herbaceous layer: 80%, *Poa spp.* 85%, *Pteridophyte*, spp. 10%, (5%) di *Acer opalus* Mill., *Fraxinus ornus* L., *Quercus cerris* L. seedlings; Parent material: Calcareous landslide; Parent rock: whitish micritic limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn+OLv+OH	1-0	1-2	C, W	-	-	-	-	-	-	-
AB	0-4	3.5-4	C, W	7.5 YR 4/3	3 vf, f, sbk	mp	Clay	3 vf, f	5	-
Bw	4-14	10-10.5	C, W	7.5 YR 4/3	3 vf, f, sbk, abk	mp	Clay	2 vf, f; 1 m	15	Stone line
AB_b	14-25	9-11	C, W	7.5 YR 5/4	3 vf, f, abk	mp	Clay	2 vf, f	60	-
Bw_b	25-45+	-	-	7.5 YR 5/4	3 vf, sbk	mp	Clay	2 vf, f, m; 1 vc	70	-

Plot T38b/Profile 1 (Gauss Boaga Rome 40 4796878 N, 2365730 E). Slope: 30%. Exposure: NO. Altitude: 830-900 m a.s.l. - Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Turkey oak high stand. Emerging rock: -. Soil cover: <5%. Vegetation. Trees: 95%, *Ostrya carpinifolia* Scop. 40%, *Quercus cerris* L. 30%, *Acer opalus* Mill. 20%, *Fraxinus ornus* L. 10%, *Fagus sylvatica* L. 10%, *Laburnum anagyroides* Medik., *Sorbus aria* (L.) Crantz. Bushes: 40%, *Corylus avellana* L. 30%, *Coronilla* L., *Crataegus monogyna* Jacq., *Cytisus* L., *Juniperus oxycedrus* L., *Rosa* L., *Ruscus aculeatus* L., suckers of *Acer opalus* Mill., *Fagus sylvatica* L., *Fraxinus ornus* L. 70%, Copertura erbacea: 50%, (70%) *Poaceae*, (20%) *Carduus* L., *Euphorbia* L., *Fragaria vesca* L., *Galium* L., *Hepatica nobilis* Schreb., *Viola* L., (10%) rinnovazione di *Acer opalus* Mill., *Fagus sylvatica* L., *Fraxinus ornus* L., *Quercus cerris* L. Parent material: Calcareous landslide; Parent rock: whitish micritic limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn+OLv+OH	2.5-0	2.5	C, S	-	-	-	-	1 vf, f	-	-
A	0-0.5	0.5-2	A, S	7.5 YR 3/2	3 vf, sbk	fi	Clay	2 vf, f	2	-
Bw	0.5-17	13-16.5	C, W	7.5 YR 4/4	3 vf, f, sbk	mp	Clay	2 vf, f; 1 m	10	-

Bw1$_b$	17-24	5-7	C, W	7.5 YR 5/6	3 f, sbk	mp	Clay	2 vf, f; 1 c	40	Stone line, organic matter accumulation
Bw2$_b$	24-33	2-9	C, W	7.5 YR 5/6	3 vf, f, sbk	mp	Clay	2 vf, f; 1 m	45	-
BC$_b$	33-40+	-	-	7.5 YR 5/6	2 vf, f, sbk	mp	Clay	1 vf, f	50	-

Plot T38b/Profile 2 (Gauss Boaga Rome 40 4796878 N, 2365730 E) Slope: 30%. Exposure: NO. Altitude: 830-900 m a.s.l. - Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Turkey oak high stand. Emerging rock: -. Soil cover: <5%. Vegetation. Trees: 95%, *Ostrya carpinifolia* Scop. 40%, *Quercus cerris* L. 30%, *Acer opalus* Mill. 20%, *Fraxinus ornus* L. 10%, *Fagus sylvatica* L. 10%, *Laburnum anagyroides* Medik., *Sorbus aria* (L.) Crantz. Bushes: 40%, *Corylus avellana* L. 30%, *Coronilla* L., *Crataegus monogyna* Jacq., *Cytisus* L., *Juniperus oxycedrus* L., *Rosa* L., *Ruscus aculeatus* L., suckers of *Acer opalus* Mill., *Fagus sylvatica* L., *Fraxinus ornus* L. 70%, Copertura erbacea: 50%, (70%) *Poaceae*, (20%) *Carduus* L., *Euphorbia* L., *Fragaria vesca* L., *Galium* L., *Hepatica nobilis* Schreb., *Viola* L., (10%) rinnovazione di *Acer opalus* Mill., *Fagus sylvatica* L., *Fraxinus ornus* L., *Quercus cerris* L. Parent material: Calcareous landslide; Parent rock: whitish micritic limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	7-2	4-9	C, W	-	-	-	-	-	-	-
OLv+OH	2-0	1-3	C, W	-	-	-	-	-	-	-
A	0-2	2-4	C, W	10 YR 2/2	3 vf, f gr; 3 vf, f, sbk	fr	Clay	3 vf, f; 1 m, c	20	-
AB	2-6	2-5	C, W	10 YR 3/2	3 vf, f, sbk	fr	Clay	3 vf, f	20	-
Bw	6-20	13-16	C, W	10 YR 3/4	3 vf, f, m, sbk	fr	Clay	3 vf, f	50	Popping aggregates, stone line
Bw1$_b$	20-40	18-20	C, W	10 YR 4/4	3 vf, f, sbk	mp	Clay	3 vf, f, m	70	-
Bw2$_b$	40-43+	-	-	-	-	-	-	-	-	Rock debris

Plot T41a Profile 1 (Gauss Boaga Rome 40 4797677 N, 2366674 E) Slope: 60%. Exposure: N. Altitude: 748-838 m a.s.l. - Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Hornbeam and manna ash coppice. Emerging rock: 15%. Soil cover: 90%. Vegetation. Trees: 90%, *Ostrya carpinifolia* Scop. 25%, *Acer opalus* Mill. 20%, *Fraxinus ornus* L. 20%, *Quercus cerris* L. 20%, *Acer pseudoplatanus* L. 5%, *Acer monspessulanum* L. (sporadic). Bushes: 10%, *Cornus mas* L. 40%, *Crataegus monogyna* Jacq. 30%, *Lonicera caprifolium* L. 30%, novellame *Acer opalus* Mill. e *Fraxinus ornus* L. 20%. Herbaceous layer: 30%, *Hedera helix* L., *Hepatica nobilis*

Schreb., *Lathyrus venetus* Mill., *Luzula nivea* L., *Polypodium vulgare* L., *Viola* L., rinnovazione di *Acer opalus* Mill., *Fraxinus ornus* L., *Sorbus aria* (L.) Crantz (10%). Parent material: Calcareous landslide; Parent rock: massive limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn+OLv+OH	3-0	-	C, W	-	-	-	-	3 vf, f	2	-
A	0-5	3-5	C, W	10 YR 2/2	3 vf, f, sbk	fr	Clay	3 vf, f; 1 m	2	-
Bw1	5-11	6-8	C, W	10 YR 3/3	3 vf, f, sbk	fr	Clay	3 vf, f; 2 m, vc	5	-
Bw2	11-19	8-9	C, W	10 YR 3/3	3 vf, f, sbk	fr	Clay	3 vf, f; 2 m; 1 c	10	-
Bw3	19-28	10-11	C, W	10 YR 3/3	3 vf, f, sbk	fr	Clay	3 vf, f; 1 m	20	-
BC	28-40+	-	.	10 YR 3/3	3 vf, f, sbk	fr	Clay	3 vf, f; 1 m	60	-

Plot T41a Profile 2 (Gauss Boaga Rome 40 4797677 N, 2366674 E). Slope: 60%. Exposure: N. Altitude: 748-838 m a.s.l. - Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Hornbeam and manna ash coppice. Emerging rock: 15%. Soil cover: 90%. Vegetation. Trees: 90%, *Ostrya carpinifolia* Scop. 25%, *Acer opalus* Mill. 20%, *Fraxinus ornus* L. 20%, *Quercus cerris* L. 20%, *Acer pseudoplatanus* L. 5%, *Acer monspessulanum* L. (sporadic). Bushes: 10%, *Cornus mas* L. 40%, *Crataegus monogyna* Jacq. 30%, *Lonicera caprifolium* L. 30%, novellame *Acer opalus* Mill. e *Fraxinus ornus* L. 20%. Herbaceous layer: 30%, *Hedera helix* L., *Hepatica nobilis* Schreb., *Lathyrus venetus* Mill., *Luzula nivea* L., *Polypodium vulgare* L., *Viola* L., rinnovazione di *Acer opalus* Mill., *Fraxinus ornus* L., *Sorbus aria* (L.) Crantz (10%). Parent material: Calcareous landslide; Parent rock: massive limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	3-1	1-3	-	-	-	-	-	-	-	-
OLv+OH	1-0		C, W	-	-	-	-	-	-	-
A	0-6	5-8	C, W	10 YR 2/2	3 vf, f, sbk	fr	Clay	3 vf, f	2	-
Bw	6-22	9-16	C, W	10 YR 3/4	3 vf, f, sbk	fr	Clay	3 vf, f; 2 m; 1 vc, c	20	-

BC	22-41+	-	-	10 YR 3/4	3 vf, f, m sbk	fr	Clay	3 vf, f; 2 m; 1 vc, c	45	-

Plot T42b/Profile 1 (Gauss Boaga Rome 40 4804219 N, 1833709 E) Slope: 40%. Exposure: N. Altitude: 695-775 m a.s.l. - Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Hornbeam and manna ash coppice. Emerging rock: 20%. Soil cover: 90%. Vegetation. Trees: 90%, *Fraxinus ornus* L. 45%, *Ostrya carpinifolia* Scop. 45%, *Acer opalus* Mill. 10%, *Quercus cerris* L., *Sorbus aria* (L.) Crantz. Bushes: 10%, *Crataegus monogyna* Jacq., *Lonicera caprifolium* L. Herbaceous layer: 30%, *Poaceae*, *Cyclamen* L., *Hedera helix* L., *Hepatica nobilis* Schreb. Parent material: Calcareous landslide; Parent rock: massive limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	3-2	0.5-2	-	-	-	-	-	-	-	-
OLv+OH	2-0	1.5-2.5	C, W	-	3 gr	-	-	-	2	-
Bw1	0-7	3-7	C, W	10 YR 4/3	3 vf, f, m, sbk, abk	fr	Clay-loam	3 vf, f; 1 m	2	-
Bw2	7-21	6-16	C, W	10 YR 4/2	3 vf, f, m, c, sbk	mh	Clay-loam	3 vf, f; 2 m	30	Secondary carbonates
BC	21-35+	-	-	-	-	-	-	3 vf, f	65	-

Plot T42b/Profile 2 (Gauss Boaga Rome 40 4804219 N, 1833709 E) Slope: 40%. Exposure: N. Altitude: 695-775 m a.s.l. - Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Hornbeam and manna ash coppice. Emerging rock: 20%. Soil cover: 90%. Vegetation. Trees: 90%, *Fraxinus ornus* L. 45%, *Ostrya carpinifolia* Scop. 45%, *Acer opalus* Mill. 10%, *Quercus cerris* L., *Sorbus aria* (L.) Crantz. Bushes: 10%, *Crataegus monogyna* Jacq., *Lonicera caprifolium* L. Herbaceous layer: 30%, *Poaceae*, *Cyclamen* L., *Hedera helix* L., *Hepatica nobilis* Schreb. Parent material: Calcareous landslide; Parent rock: massive limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	3-2	-	C, W	-	-	-	-	-	-	-
OLv+OH	2-0	-	C, W	-	-	-	-	-	5	-
A	0-3	1-3	C, W	10 YR 2/2	3 vf, f, sbk	fr	Clay-loam	3 vf, f	5	-
Bw	3-18	13-19	C, W	10 YR 3/2	3 vf, f, sbk	mh	Clay-loam	3 vf, f; 2 m; 1 c	60	Secondary carbonates

BC	18-35+	-	-	-	-	-	-	2 vf, f; 1 c	75	-

PlotT42c/Profile 1 (Gauss Boaga Rome 40 1835654 N, 13.154697 E) Slope: 40%. Exposure: N. Altitude: 690-780 m a.s.l. - Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Hornbeam and manna ash coppice. Emerging rock: 15%. Soil cover: sporadic litter presence. Vegetation. Trees: 80%, *Quercus cerris* L standards. Bushes: 5%, *Prunus spinosa* L., suckers of *Acer opalus* Mill., *Fraxinus ornus* L., *Ostrya carpinifolia* Scop., *Sorbus aria* (L.) Crantz. Herbaceous layer: 90%, *Poaceae*, *Cyclamen* L., *Daphne* L., *Fragaria vesca* L., *Hedera helix* L., *Helleborus Tourn*., *Lamium maculatum* L. Parent material: Calcareous landslide; Parent rock: whitish micritic limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	-	-	-	-	-	-	-		-	Sporadic
OLv+OH	1-0	1-1.5	C, W	-	3 gr	-	-	3 vf, f; 1 c	2	-
A	0-4	2-4	C, W	7.5 YR 3/2	3 vf, f, sbk	fr	Clay-loam	3 vf, f; 1 m	2	-
BC	4-21	16-22	C, W	7.5 YR 3/4	3 vf, f, m, sbk, abk	fr	Clay-loam	3 vf, f; 1 m, c	60	Pendular secondary carbonates
C	21-35+	-	-	-	-	-	-	2 vf, f	75	-

PlotT42c/Profile 2 (Gauss Boaga Rome 40 1835643 N, 13.154690 E) Slope: 40%. Exposure: N. Altitude: 690-780 m a.s.l. - Mean annual air temperature: 13.5°C – Mean annual precipitation: 750 mm. Management: Hornbeam and manna ash coppice. Emerging rock: 15%. Soil cover: sporadic litter presence. Vegetation. Trees: 80%, *Quercus cerris* L standards. Bushes: 5%, *Prunus spinosa* L., suckers of *Acer opalus* Mill., *Fraxinus ornus* L., *Ostrya carpinifolia* Scop., *Sorbus aria* (L.) Crantz. Herbaceous layer: 90%, *Poaceae*, *Cyclamen* L., *Daphne* L., *Fragaria vesca* L., *Hedera helix* L., *Helleborus Tourn*., *Lamium maculatum* L. Parent material: Calcareous landslide; Parent rock: whitish micritic limestone. **Soil** (Soil Survey Staff, 2014): Humus Lithic Eutrudept

OLn	-	-	-	-	-	-	-	-	-	Sporadic
OLv	4-0	1-4	C, W	-	-	-	-	-	-	-
A	-	-	-	-	-	-	-	-	-	Sporadic
Bw1	0-6	6-7	C, W	10 YR 3/3	3 vf, f, m, sbk	fr	Clay-loam	3 vf, f;	20	Pendular secondary

								1 m		carbonates
Bw2	6-15	9-12	C, W	10 YR 3/3	3 vf, f, m, sbk	fr	Clay-loam	2 vf, f; 1 m	40	-
C	15-35+	-	.	-		-	-	-	80	-

[a] designation according to Baize et al. (2008) for organic horizons, to Schoeneberger et al. (2012) for mineral horizons.

[b] A = abrupt; V = very abrupt; C = clear; G = gradual; S = smooth; W = weavy; I = irregular; B = broken.

[c] moist and crushed, according to the Munsell Soil Color Charts.

[d] The reported values are the average content for the horizon considered.

[f] 1 = weak; 2 = moderate; 3 = strong. f = fine; m = medium; c = coarse. gr =granular; abk = angular blocky; sbk = sub-angular blocky; sg = single grain.

[g] br = brittle; fi = firm; fr = friable; mh = moderately hard; mp = moderately plastic; ms = moderately sticky; sh = slightly hard; sp = slightly plastic; vfr = very friable.

[h] 0 = absent; 1 = few; 2 = plentiful; 3 = abundant. vf = very fine; f = fine; m = medium; c = coarse; vc = very coarse

CHAPTER 5 - IMPACT OF DIFFERENTIATED FOREST MANAGEMENT ON SOIL ORGANIC MATTER FRACTIONS C STORAGE CAPACITY

1. Introduction

One of the roles of soil is to provide nutrients to global ecosystems via bio-cycling processes (McLauchlan, 2006). This is related to its physical and chemical properties, which make it able to support life in its multiform manifestations, both autotrophic and heterotrophic, and consequently generate trophic chains (Pereira et al, 2018.). Nowadays, the increasing interest in climate change dynamics and in the role of the carbon cycle in this process, make the soil an important study subject for its capacity to store C (Angst et al., 2018; Lou et al., 2019). Starting from the inputs of organic matter coming from plants decaying parts, through the pedofauna and microorganisms' biological activity, organic carbon assumes a more and more recalcitrant form (e.g., humic substances) (Hayes et al., 2020). All these processes allow the soil to constitute a stable and not very reactive carbon reservoir, particularly in deep horizons (Fontaine et al., 2007).

Human presence had influenced Earth's landscape for millennia (Braje & Erlandson, 2013), in particular in the last two centuries the increase of production activity has fostered much more intense exploitation of energetic resources (Wang, 2021). In this optical a huge part of global forests has been subjected to intense management for different production purposes (e.g., energetic biomasses, building materials, and food) with a consequent impact on soils (Jie et al., 2002.). In Europe, in particular, a high percentage of forests underwent a complete management change into arable lands (Fyfe et al., 2015). In this historical context, sweet chestnut (*Castanea sativa* Mill.) has represented a link between different production necessities in the Mediterranean basin (Condera et al., 2004). Different studies have shown the influence of chestnut forests management on soil properties (Venanzi et al., 2016; Sun et al., 2019; De Feudis et al., 2020), but a lack of information exists in terms of evaluating the influence of chestnut forest management on soil organic C and stock. Thus, the present work is focused on monitoring, during two different years, the variation of organic C soil stock in litter and in three organic matter density fractions (water extractable, particulate, and mineral associated) until 30 cm depth in mineral soil under a chestnut forest subjected to different management practices: i) secular marroni productive groove, ii) chestnut forest in conversion to marroni groove iii) natural evolution chestnut forest.

2. Materials and methods

2.1 Study site description

Three soils under a 5 hectares chestnut forest were selected in a hilly internal area of the Marche Region near Pievebovigliana village in Macerata province. The site is located between 770 and 820 m above sea level (a.s.l.) with a mean annual precipitation (MAP) of about 900 mm and a mean annual air temperature (MAAT) of 13.0 C°. These soils developed on molasse rocks (sandstone interbedded with siltstone layers) as parent material. The forest, dominated by the presence of Chestnut trees, is subjected to different management: *i)* a centuries-old marroni productive groove (MAR); *ii)* a recent (two-year) converted chestnut groove into a productive marroni groove (CHEST-CONV); *iii)* a chestnut groove for chestnut flour production (CHEST) (Figure 1).

MAR plot presents a soil micromorphology characterized by big embarkments made approximately 150 years ago that soften the slope to 25-38%. The tree's density is about 70 plants per hectare and most of them are secular individuals. CHEST-CONV plot is situated in the upper part of a slope with a slope ranging from 35 to 42% with a tree density of 150 plants per hectare subjected to a graft operation in 2018. CHEST plot is located in the lower part of a slope in continuity with the CHEST-CONV plot with a slope ranging from 38 to 45%. All the areas were subjected to an intensive practice of litter layers asportation during past centuries for sustenance purposes (e.g. livestock feeding).

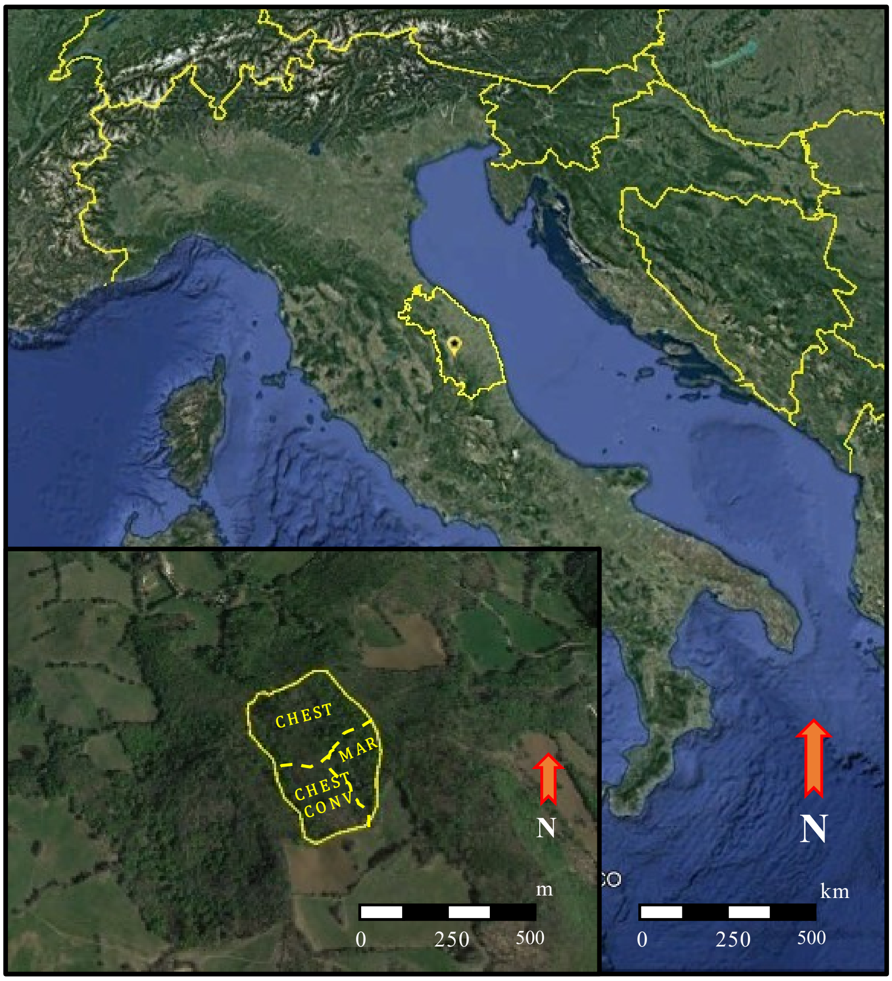


Figure 1. Study site geographical position and plots distribution

2.2 Soil trenching, morphological description, sampling, analysis and stock calculation

In November 2019, a geomorphological and soil survey was conducted in each assay parcel, through the opening of several mini-pits and auger holes, to choose the most representative position where to dig the soil profile. After this evaluation, three soil replicate profiles were dug during every annual sampling campaign in the same season and at the same topographic conditions.

Following the protocol reported by Camponi et al. (2022), each soil profile was dug at ≈1 m downslope of the stem of one of the oldest trees present in the sampling area and until the depth of ≈50 cm. The forest floor was described according to Baize et al. (2008) and sampled in an area of about 3-4 m^2 around the profile. The mineral horizons were described per USDA "Field book for describing and sampling soils" (Schoeneberger et al., 2012). All the information about soil morphology and a general description of the areas are provided in Table 1.

Soil was sampled and evaluated for its bulk density by each genetic horizon following Camponi et. al (2022). Field samples were refrigerated until they arrive in the laboratory, where were air-dried. All samples and soil cores were sieved at 2 mm to separate the fine earth from the skeleton.

The particle-size analysis of mineral soil samples was determined by the Pipette method (Gee & Or, 2002). The mineralogical analysis (QXRD) was accomplished according to Agnelli et al., 2021 by a Philips PW 1830 x-ray diffractometer, using the Fe-filtered Kα1 radiation of Co, and operating at 35 kV and 25 mA; the step size was 0.02° 2θ and scanning speed was 1 s per step. For all samples, diffractograms were acquired on powdered and manually compressed aliquots and mineralogical composition was obtained by identifying the minerals based on their characteristic peaks. For each sample, a semi-quantitative estimation was obtained by calculating the area produced by the primary peak of each mineral by multiplying the peak height by the base at the half-height. The bulk density of mineral samples was determined by the core method (Grossman and Reinsch, 2002). For the organic horizons, the bulk density was estimated by pedotransfer-functions (Hollis et al., 1996). The soil organic matter (SOM) fractionation was made by density-based method with sodium polytungstate (SPT) for particulated organic matter (POM) and mineral associated organic matter (MAOM) fractions (Plaza et al., 2019), while water extractable organic matter (WEOM) was extracted after one night of the 1:10 solid:liquid suspension in an orbital shaker at 140 rpm and filtered through a Whatman 42 filters (Agnelli et al., 2014). Soil reaction (pH) was determined potentiometrically by Thomas (1996). Total organic carbon (TOC) on soil samples and on SOM fractions (WEOC, POC and MAOC) was estimated by Walkley-Black method (Nelson & Sommers, L.E, 1996).

Table 1. General features and morphology of the mean profile of each management thesis under *Castanea sativa* L. Monte San Savino, Pievebovigliana, Marche, Italy. For symbols see legend. Mean annual air temperature and rainfall in 1991-2010 period: mean annual total precipitation, 945 mm; mean annual air temperature, 13°C. Average altitude 820 m a.s.l.. Vegetation – Trees: *Ostrya carpinifolia* L., *Populus tremula* L. Bushes: *Rubus ulmifolius* L., *Crataegus monogyna* L.; Herbaceous layer: *Ciclamen spp.*; Soil: Typic Dystrustept (Soil Survey Staff, 2014).

Tier	Horizons[a]	Depth[b]	Thickness[c]	Colour[d]	Structure[e]	Consistence[f]	Roots[g]	Boundary[h]	Skeleton[i]	Other observations
		cm	cm						%	
Management: non-productive chestnut forest *Parent material: Sandstone interbedded with siltstone layer; mean slope: 38-45 %; exposure: from N to NW; average soil cover 100 % (chestnut 80%, other 20%)*										
Organic	OLn; OLv; OF; OH	8.0/1.0-0	2.5-5.5	-	2/3, gr	fr	2, vf, 1, f	cw	-	Leaves, branches, urchins and chestnuts
Organo-mineral	A; AB	0-2.0/9.0	2.0-5.0	2.5Y 3/3 10YR 1/2 10YR 2/1	2, sbk, f, m, co	fr	3, vf, 1 f	cw	-	Mesofauna and mycelium
Mineral	Bw; Bg; C	2.0/9.0-106/120+	19.0-23.0	10YR 4/6-5/6-5/8 2.5 Y 6/6	2, sbk, abk, f, m co	fr	1, vf, 2, f, 3, co, m	cw	-	Lessivage salt-and-pepper effect on aggregates, cutans, Mn hydroxides, roots channels
Management: non-productive chestnut forest in conversion to marroni grove *Parent material: Sandstone interbedded with siltstone layers; mean slope: 25-35 %; exposure: from N to NW; average soil cover 80 % (chestnut 60%, other 40%)*										
Organic	OLn; OLv; OF; OH	7.0/4.5-0	3.0-2.0	-	2, sbk, gr, f	fr	2, vf,1, f	cw cb aw	-	Leaves, branhces, urchins and chestnuts
Organo-mineral	A; AB	0-1.0/5.0	3.0-6.0	10YR 2/1-3/2	2 gr 2, abk, m, f	fr	2, vf, f	cw	-	Mesofauna
Mineral	Bw; Bg; C	0-93.0/115.0+	21.0-54.0	10YR 2/1-4/6-5/6 2.5 Y 5/6	2, sbk, abk, co, m	fr	2, vf,1, f 3, co, m	cw	-	Charcoal fragments, lessivage salt-and-pepper effect on aggregates, cutans, mottles, Mn hydroxides, roots

										channels
Management: marroni grove										
Parent material: Sandstone interbedded with siltstone layer; mean slope: 10-20 %; exposure: from N to NW; average soil cover 70 % (chestnut 100%)										
Organic	OLn; OLv; OF; OH	5.5/7.0-0	2.5-6.0	-	2 gr	-	2, vf,1, f	cw	-	Leaves, branches, urchins and chestnuts
Organo-mineral	AB; AB&B	0-5.0/17.0	7.5-13.0	2.5Y 3/3 10YR 3/4-4/6	2-3, sbk, m, f	fr	2, vf,1, f	cw	-	Earthworms and mycelium
Mineral	Ab; Bwb; Bw	5.0/17.0-20.0/108.0+	21.0-30.0	10YR 3/4-3/6-4/6-5/8	2, sbk, abk, co, m	fr	2, vf, 3, co, m, f	cw ci ab	-	Lessivage salt-and-pepper effect on aggregates, cutans, mottles, Mn hydroxides, roots channels

[a] Horizons: designation according to Baize et al. (2008) for organic horizons, to Schoeneberger et al. (2012) for mineral horizons.

[b] Depth: numbers separated by slash (/) indicate the range of depths observed in the profiles, while the hyphen (-) means “from (what is before it) to (what is after it)”.

[c] Thickness: referred to the lowest and highest mean thickness.

[d] Colour: moist and crushed, according to the Munsell Soil Color Charts. The reported colours are the extremes for the horizons considered.

[e] Structure: 1=weak, 2=moderate, 3=strong; th=thin, f=fine, m=medium, c=coarse; gr=granular, abk=angular blocky, sbk=sub-angular blocky, pl=platy. The reported structures are the extremes for the horizons considered.

[f] Consistence: fr=friable, fi=firm.

[g] Roots: 0=absent, v_1=very few, 1=few, 2=plentiful, 3=abundant; mi=micro, vf=very fine, f=fine, m=medium, co=coarse. The reported roots abundances are the extremes for the horizons considered.

[h] Boundary: a=abrupt, c=clear; g=gradual; d=diffuse; s=smooth; w=weavy; i=irregular; b=broken.

[i] Skeleton: by sight, according to the “percent of area covered” tables reported in Schoeneberger et al. (2012). The reported values are the extremes for the horizons considered.

2.6 Data treatment and statistical analysis

According to the soil variability genetic horizons were grouped relying on their nature into the following soil tiers: *i*) organic (O), made of well-expressed OL (OLn, OLv), OF and OH horizons; *ii*) organo-mineral (OM), grouping A, AB, AB&B horizons; and *iii*) mineral (M), formed by Ab, Bw, Bwb, Bg, and C horizons (Table 1). The properties of the soil tiers are the thickness-based weighed mean of each property. The element stocks for the litter and for soil organic matter fractions in 0-30 cm soil layer were calculated adding up the contribution of each genetic horizon considering their thicknesses. The differences among samples were tested by one-way or two-way ANOVA depending on the variable took into account (year, management or horizon tier) and the interaction between them. Prior to ANOVA, normality and homoscedasticity of the dataset were assessed using Shapiro-Wilk statistical test and by Levene's test at 5% significance level, respectively. Assumptions were not violated and Duncan's multiple range test was used to determine the significant differences between samples at $P \leq 0.05$.

3. Results

3.1 Soil morphology

The studied soils were classified as Typic Dystrustept and showed a total depth greater than 100 cm with a considerable number of well-expressed weathered B horizons that constituted the majority of the pedon and a negligible amount of rock fragments. All the informations reported in this chapter are reported in Table 1.

CHEST plot soil in general showed a moderate developed forest floor (2.5-5.5 cm) in OLn, OLv, OF and OH horizons principally constituted by chestnut leaves, branches and chestnuts. The OH horizons showed a good to moderate crumble friable structure with a moderate to low amount of very fine and fine roots. The OM tier (2.0-5.0 cm average thickness) horizons showed a moderate fine to coarse sub-angular friable blocky structure with many very fine roots, few fine roots, an active presence of mesofauna and a good amount of fungal hyphae. The M tier horizons were well-developed in angular to sub-angular fine to coarse friable blocky with an average thickness that ranged from 19.0 to 23.0 cm. In this soil tier were noticed the presence of fine particles engulfed horizons (Bg) characterized by clay cutans on soil aggregates, mottling pattern ("salt and pepper" morphology) by lessivage process and Mn hydroxides nodules. In general the roots amount in this tier is abundant and represented in majority by coarse and medium size roots.

The CHEST-CONV plot showed a well-developed soil with an O tier formed by chestnut leaves, small branches, urchins and fruits at different degradation states. The OH horizon showed a well-expressed granular and friable structure with a pour to good amount of very fine/fine roots. OM tiers horizons showed an average thickness of 3.0 to 6.0 cm with a moderate granular to medium and fine angular blocky. Roots amount on average is good and represented by very fine and fine elements. In all the horizons were noticed a mesofauna activity. M tier horizons were developed in sub-angular to angular medium to coarse friable blocky, with an average thickness that ranged from 21.0 to 54.0 cm. In this soil tier were noticed the presence of charcoal fragments and as CHEST plot Bg horizons. Roots amount varied from abundant (medium and coarse) to common and few respectively for very fine and fine elements.

MAR plot soils showed a moderately developed forest floor (2.5-6.0 cm) in OLn, OLv, OF and OH horizons principally constituted by chestnut leaves, branches, urchins and chestnuts. The OH horizons showed a good granular structure with a moderate to few amount of very fine and fine roots. The OM tier (7.5-13.0 cm average thickness) horizons showed a strong to moderate fine to medium sub-angular friable blocky structure with a moderate amount of very fine roots and few fine roots. In this tier were noticed an active presence of earthworms and a good amount of fungal hyphae. The M tier horizons were well-developed in angular to sub-angular medium to coarse friable blocky structure with an average thickness that ranged from 21.0 to 30.0 cm. This soil tier was characterized by the presence of buried horizons (Ab and Bwb) that testify to past mass movements. In the deeper horizons of the tier were observed fine particles engulfments, clay cutans on soil peds, “salt and pepper” morphology by lessivage process and Mn hydroxides nodules. The fine to coarse roots are abundant while very fine roots were observed in a smaller amount.

3.2 Physicochemical soil properties and organic C stocks

The particle size distribution displayed in general a high presence of coarse particles in all the surveyed soils with the highest sand content in the CHEST plot that showed a loamy-sand to sandy-clay-loam texture while CHEST-CONV and MAR plots showed similar behavior in both OM and M horizons with a sandy-clay-loam texture. In all the surveyed soil it is common a higher fine particles (silt and clay) in M horizon (Table 2).

The QXRD revealed in general scarcity of minerals useful for plants’ nutrient uptake. A huge amount of quartz (from 48 to 63%) in the form of quartzite and a higher content of plagioclases were revealed in the CHEST plot than in the other plots. QXRD further revealed a higher content of Orthoclase in OM horizons than in M horizons while the opposite behaviour is displayed for Albite and clay minerals (Table 2).

No differences were recorded in the depth of litter layer measurements nor among the management plots or among years. pH showed in general to be slightly acidic (from 5.44 to 6.12) with higher values in CHEST-CONV for both sampling campaign years. Bulk density remains unvaried during the two years of the monitoring program, while inside each plot the highest values were recorded in the M tiers and the lowest in the O tiers, a normal behaviour as a function of increasing pressure along soil profile. TOC amount varied along soil profile (decreasing from O to M horizon tiers), among management plots but not in time, in particular, it was recorded a higher amount in CHEST-CONV and MAR than in CHEST plot (Table 3).

The SOM fractionation (Table 4) highlighted a generally unchanged trend from the first to the second year except for the WEOC and POC $\rho > 1.6$ gdm^{-3} amount of OM tiers in the CHEST-CONV plot that tent to decrease and MAOC amount of the M tiers in the MAR plot that tent to increase. WEOC content inside each management plot showed a higher amount in the OM than the M tiers in both years, while MAOC content varied depending on the plot and the year with higher content in OM than M tiers in CHEST and MAR plots during the first year. POC $1<\rho<1.6$ gdm^{-3} amount displayed relevant differences for CHEST-CONV plot in the I year and MAR plot in the II year. The organic C stock in 0-30 cm depth layer showed a higher storage in the second year in general for all the management plots for TOC, WEOC and MAOC fractions, while litter and POC fraction stocks did not show variations during the two surveyed years (Table 5).

Table 2 – Values of particle size distribution and mineralogy in two soil tier typologies (organo-mineral and mineral) under chestnut forest subjected to different management (Pievebovigliana, Marche region, Italy). Numbers in parentheses are the standard deviations. Capital letters indicate differences within management and lowercase letters between tiers of the same management. at P <0.05 level of significance.

Manag	Tier	Particle size distribution[a]														Mineralogy[b]											
		Sand									Silt		Clay			Qu	Pl		Alb		Cal	Ka	Or		Mi	CM	
		CO			M			F		VF																	
		gkg^{-1}														%											
Chest	Org-min	318 (106)	a	A	160 (48)	a	A	206 (22)	A	120 (42)	66 (26)	b	130 (33)	b	A	53 (10)	22 (12)	A	15 (10)	b	- -	- -	5 -	a	2 (3)	5 (7)	b
	Min	68 (27)	b		105 (25)	b		258 (40)		145 (27)	178 (26)	a	246 (36)	a		50 (8)	14 (8)		23 (3)	a	- -	3 (3)	3 (3)	b	3 (3)	9 (8)	a
Chest-conv	Org-min	204 (105)	a	B	110 (25)	a	B	247 (18)	B	138 (50)	126 (52)	b	175 (46)	b	B	48 (4)	8 (11)	B	18 (4)	b	- -	- -	10 (0)	a	- -	13 (4)	b
	Min	65 (47)	b		94 (30)	b		230 (37)		166 (31)	184 (51)	a	261 (28)	a		53 (8)	3 (6)		22 (16)	a	- -	- -	5 (5)	b	- -	17 (3)	a
Mar	Org-min	124 (32)	a	B	90 (13)	a	B	341 (45)	B	150 (14)	127 (25)	b	168 (32)	b	B	63 (8)	15 (5)	AB	7 (8)	b	- -	- -	7 (3)	a	2 (3)	- -	b
	Min	44 (19)	b		96 (16)	b		355 (56)		142 (16)	155 (27)	a	208 (34)	a		53 (6)	6 (5)		23 (6)	a	- -	3 (3)	1 (3)	b	3 (3)	13 (9)	a

[a] CO: coarse; M: medium; F: fine; VF: very fine

[b] Qu: quartzite; Pl: plagioclase; Alb: albite; Cal: calcite; Ka: kaolinite; Or: orthoclase; Mi: micas; CM: clay minerals

Table 3 – Values of pH, bulk density, litter depth and total organic carbon (TOC) in three soil tier typologies (organic, organo-mineral and mineral) over two years under chestnut forest subjected to different management practice in Pieveboviglina site. Numbers in parentheses are the standard deviations. Single quote marks in boxes indicate differences within tiers and different capital letters indicate differences within management at *P* <0.05 level of significance. No letters in boxes indicate no differences for the parameters nor in management, tier type or interaction tier type x year.

Management	Tier	1st year Litter depth cm	pH		Bulk density $kgdm^{-3}$	TOC gkg^{-1}		2nd year Litter depth cm	Bulk density $kgdm^{-3}$	pH		TOC gkg^{-1}	
Chest	Org		5.84 (0.26)		0.72^{C} (0.08)	281.05^{A} (129.93)			0.77^{C} (0.09)	5.34 (0.82)		359.61^{A} (145.84)	
	Org-min	2.90 (2.20)	6.12 (0.27)	AB	0.84^{B} (0.18)	57.94^{B} (37.28)	B	2.17 (1.15)	1.29^{B} (0)	6.18 (0.23)	AB	80.17^{B} (1.07)	B
	Min		5.69 (0.27)		1.18^{A} (0.11)	7.90^{C} (3.98)			1.30^{A} (0.05)	5.70 (0.13)		13.57^{C} (4.06)	
Chest-conv	Org		6.11 (0.38)		0.73^{C} (0.08)	290.63^{A} (143.14)			0.80^{C} (0.05)	5.87 (0.85)		422.89^{A} (78.69)	
	Org-min	3.00 (2.20)	5.44 (0.23)	A	0.83^{B} (0.23)	75.68^{B} (40.3)	A	2.07 (0.73)	1.29^{B} (0.02)	6.25 (0.40)	A	58.26^{B} (34.84)	A
	Min		5.60 (0.25)		1.17^{A} (0.19)	9.91^{C} (8.26)			1.28^{A} (0.06)	5.73 (0.13)		15.26^{C} (4.70)	
Mar	Org		5.75 (0.38)		0.75^{C} (0.07)	330.94^{A} (121.87)			1.03^{C} (0.61)	5.30 (0.86)		425.57^{A} (50.96)	
	Org-min	3.70 (2.50)	5.67 (0.39)	B	0.91^{B} (0.11)	38.62^{B} (22.62)	A	2.07 (0.73)	1.30 -	5.41 (0)	B	76.41 -	A
	Min		5.67 (0.15)		1.18^{A} (0.18)	7.00^{C} (0.93)			1.26^{A} (0.15)	5.58 (0.24)		19.06^{C} (14.23)	

Table 4 - Values of fractionated organic carbon in two soil tiers (organo-mineral and mineral) over two years under chestnut forest subjected to different management in the Pievebovigliana site. Numbers in parentheses are the standard deviations. Capital letters indicate differences in the same tier of the same management in different years, lowercase letters indicate differences within tiers in the same management in the same year at *P* <0.05 level of significance.

	Year	Tier	WEOC*		POC** ρ<1 gdm^{-3}		POC** 1<ρ<1.6 gdm^{-3}		POC** ρ >1.6 gdm^{-3}		MAOC***	
			gkg^{-1}									
Chest	1°	Org-Min	2.43	aA	9.39	A	30.55	A	18.13	A	15.53	aA
			(0.96)		(10.26)		(37.75)		(15.49)		(11.36)	
		Min	1.89	bA	u.d.l.		u.d.l.		u.d.l.		5.90	bA
			(0.21)		-		-		-		(3.80)	
	2°	Org-Min	2.66	aA	7.48	A	25.70	A	20.29	A	24.03	aA
			(0.63)		(3.72)		(21.08)		(8.49)		(19.98)	
		Min	1.67	bA	u.d.l.		u.d.l.		u.d.l.		11.91	aA
			(0.10)		-		-		-		(4.11)	
Chest-Conv	1°	Org-Min	3.49	aA	5.81	A	7.40	A	19.39	A	39.59	aA
			(0.10)		(3.97)		(1.74)		(5.28)		(39.77)	
		Min	1.97	bA	u.d.l.		u.d.l.		u.d.l.		7.94	aA
			(0.15)		-		-		-		(8.19)	
	2°	Org-Min	2.25	aB	2.40	A	11.84	aA	5.00	B	38.44	aA
			(0.17)		(0.99)		(5.56)		(0.87)		(31.89)	
		Min	1.97	bA	5.25		2.08	b	u.d.l.		10.68	aA
			(0.30)		-		(1.24)		-		(4.75)	
Mar	1°	Org-Min	2.60	aA	3.61		9.84	a	5.50		14.98	aA
			(0.75)		(2.27)		(4.19)		(3.15)		(14.01)	
		Min	1.95	bA	u.d.l.		2.03	bA	u.d.l.		3.01	bB
			(0.13)		-		(0.99)		-		(1.04)	
	2°	Org-Min	2.26	aA	3.66		26.31		8.42		35.77	
			-		-		-		-		-	
		Min	1.85	bA	u.d.l.		4.23	A	4.67		17.34 [a]	A
			(0.15)		-		(2.70)		-		(12.57)	

* Water extractable organic carbon
** Particuleted organic carbon
*** Mineral-associated organic carbon
u.d.l: under detection limit

Table 5 – Values of total organic C (TOC) stock in litter and in mineral layer (0-30 cm) and organic C stock in soil organic matter fractions* in depth layer 0-30 cm in Pievebovigliana site. Numbers in parentheses are the standard deviations. Different capital letters indicate differences within years both at *P* <0.05 level of significance. No letters in boxes indicate no differencese for the parameters nor in management, tier type or year.

	Management	TOC			WEOC		POC			MAOC	
		Litter	0-30				ρ<1 gdm^{-3}	1<ρ<1.6 gdm^{-3}	P>1.6 gdm^{-3}		
							$Mgha^{-1}$				
I year	Chest	157.07 (25.03)	35.57 (14.79)		4.90 (2.30)		1.48 (0.89)	4.97 (3.81)	4.37 (3.29)	19.87 (6.26)	
I year	Chest-conv	169.85 (85.95)	36.92 (12.88)	B	5.05 (1.21)	B	6.79 (11.26)	2.39 (3.66)	4.17 (6.34)	25.63 (19.82)	B
I year	Mar	201.53 (26.78)	48.18 (13.38)		5.84 (0.52)		2.12 (1.93)	14.81 (3.83)	5.75 (5.6)	19.65 (5.68)	
II year	Chest	143.44 (35.13)	93.28 (16.94)		6.58 (0.93)		4.98 (2.16)	17.17 (13.15)	13.71 (5.00)	50.84 (14.58)	
II year	Chest-conv	234.83 (89.93)	85.76 (34.6)	A	7.60 (0.67)	A	4.73 (5.93)	10.77 (5.42)	1.92 (1.66)	60.74 (35.04)	A
II year	Mar	183.20 (124.23)	79.35 (13.70)		7.04 (0.68)		0.63 (1.10)	8.66 (8.82)	2.61 (4.51)	60.41 (9.37)	

* Water extractable organic carbon
** Particuleted organic carbon
*** Mineral-associated organic carbon

4. Discussions

The differences among plots in term of textural class could be attributed to the lithological diversity of the parent rock in the area that is constituted by bedded layers of coarser materials (e.g. sandstone) and finer (e.g. siltstone), thus depending on the pedogenized layer the soil texture could varied from coarser (loamy-sand) to finer one (sandy-clay-loam). Observations made on fine engulfment in depth along soil profile (e.g. Bg horizons morphology) and particle size distribution revealed a behaviour confirmed by QXRD: the higher concentration rate of silt and clay fractions in M horizon tiers and clay minerals (CM) detected in higher amount in this samples suggest a fines hydraulic transport hypothesis; similar to that shown by other authors like Jacobsen et al. (1997) that demonstrated how fine particles could be transported by a rainfall-like water flux through soil macropores in a laboratory experiment on undisturbed sandy-loam soil columns.

pH pattern among the plots could be ascribed to a site-specific relation between plant, soil and forest diversity as shown by other authors (Finzi et al., 1998; Eisalou et al., 2013; Corti et al, 2019) that highlighted how particular site conditions and plants interactions modify the pH of aqueous solutions that flow through the canopy, stems and forest floor in temperate broadleaves forests.

Soil tiers TOC showed a descending trend along soil profile that is usually observed in forest soil due to the high intake of biomass by plants litter (Mason and Zanner, 2005), while the differences among plots could be ascribed to a topographical and management combined effect that reduced the impact of erosion phenomena on soil degradation and organic matter loss, in fact, MAR and CHEST-CONV plots showed a minor steep slope than the CHEST plot and in particular in MAR plot there is a stable secular condition with presence of hydraulic-forest interventions (soil embankments) that could have favoured the conservation of top-soil compared to CHEST plot (Brezzi et al, 2016). The variability of SOM fractions in soil tiers and in time as for CHEST-CONV plot WEOC and POC ρ >1.6 gdm^{-3} and MAR plot MAOC could be ascribed to the high spatial and temporal variability that these soil components are subjected in natural and seminatural environment as shown by Schiedung et al. (2017) and Ghani et al. (2022). The organic C storage values revealed a potential lower degradation rate in 0-30 cm soil depth layer from first to second year that could not be ascribed to any of the investigated soil properties and that could be influenced by other site-specific features (e.g. soil moisture and temperature regimes).

5. Conclusions

The monitoring activity on 0-30 cm soil depth layer total and fractionated C stock conducted on an Apennines chestnut forest subjected to a differentiated management reveal a strict connection between site features, forest coenoses, soil properties and management in particular: i) texture and mineralogy showed to be influenced by transport phenomena charged to fine particles along soil profile; ii) soil reaction had a strong relation with plant biological activity and botanical diversity that could have influenced the properties of canopy, stem and litter leachate solutions; iii) TOC amounts seem to be influenced by both site characteristics and management with higher levels in CHEST-CONV and MAR plots; iv) the differences in WEOC and MAOC contents in CHEST-CONV and MAR plots could be ascribed to them characteristic of space-temporal variability; v) the variation of total and fractionated organic C stock in 0-30 cm depth layer reveals differences that could be ascribed to site-specific features that need to be investigated more in depth.

References

Agnelli, A., Bol, R., Trumbore, S.E., Dixon, L., Cocco, S., Corti, G., 2014. Carbon and nitrogen in soil and vine roots in harrowed and grass-covered vineyards. Agric. Ecosyst. Environ. 193, 70–82. https://doi.org/10.1016/j.agee.2014.04.023

Agnelli, A., Corti, G., Massaccesi, L., Ventura, S., D'Acqui, L.P., 2021. Impact of biological crusts on soil formation in polar ecosystems. Geoderma 401, 115340. https://doi.org/10.1016/j.geoderma.2021.115340

Angst, G., Messinger, J., Greiner, M., Häusler, W., Hertel, D., Kirfel, K., Kögel-Knabner, I., Leuschner, C., Rethemeyer, J., Mueller, C.W., 2018. Soil organic carbon stocks in topsoil and subsoil controlled by parent material, carbon input in the rhizosphere, and microbial-derived compounds. Soil Biol. Biochem. 122, 19–30. https://doi.org/10.1016/J.SOILBIO.2018.03.026

Brezzi, L., Bossi, G., Gabrieli, F., Marcato, G., Pastor, M., Cola, S., 2016. A new data assimilation procedure to develop a debris flow run-out model. Landslides 13, 1083–1096. https://doi.org/10.1007/s10346-015-0625-y

Braje, T.J., Erlandson, J.M., 2013. Looking forward, looking back: Humans, anthropogenic change, and the Anthropocene. Anthropocene 4, 116–121. https://doi.org/https://doi.org/10.1016/j.ancene.2014.05.002

Conedera, M., Manetti, M.C., Giudici, F., Amorini, E., 2004. Distribution and economic potential of the Sweet chestnut (*Castanea sativa* Mill.) in Europe. In: Ecologia mediterranea, tome 30 n°2. pp. 179-193; https://doi.org/10.3406/ecmed.2004.1458

Corti, G., Agnelli, A., Cocco, S., Cardelli, V., Masse, J., Courchesne, F., 2019. Soil affects throughfall and stemflow under Turkey oak (*Quercus cerris* L.). Geoderma 333, 43–56. https://doi.org/10.1016/j.geoderma.2018.07.010

De Feudis, M., Falsone, G., Vianello, G., Antisari, L.V., 2020. The conversion of abandoned chestnut forests to managed ones does not affect the soil chemical properties and improves the soil microbial biomass activity. Forests 11. https://doi.org/10.3390/F11080786

Eisalou, H.K., Şengönül, K., Gökbulak, F., Serengil, Y., Uygur, B., 2013. Effects of forest canopy cover and floor on chemical quality of water in broad leaved and coniferous forests of Istanbul, Turkey. For. Ecol. Manage. 289, 371–377. https://doi.org/10.1016/j.foreco.2012.10.031

Finzi, A.C., Van Breemen, N., Canham, C.D., 1998. Canopy tree-soil interactions within temperate forests: Species effects on soil carbon and nitrogen. Ecol. Appl. 8, 440–446. https://doi.org/10.1890/1051-0761(1998)008[0440:CTSIWT]2.0.CO;2

Fontaine, S., Barot, S., Barré, P., Bdioui, N., Mary, B., Rumpel, C., 2007. Stability of organic carbon in deep soil layers controlled by fresh carbon supply. Nature 450, 277–280. https://doi.org/10.1038/nature06275

Fyfe, R.M., Woodbridge, J., Roberts, N., 2015. From forest to farmland: Pollen-inferred land cover change across Europe using the pseudobiomization approach. Glob. Chang. Biol. 21, 1197–1212. https://doi.org/10.1111/gcb.12776

Ghani, M.I., Wang, J., Li, P., Pathan, S.I., Sial, T.A., Datta, R., Mokhtar, A., Ali, E.F., Rinklebe, J., Shaheen, S.M., Liu, M., Abdelrahman, H., 2022. Variations of soil organic carbon fractions in response to conservative vegetation successions on the Loess Plateau of China. Int. Soil Water Conserv. Res. https://doi.org/10.1016/j.iswcr.2022.05.002

Hayes, M.H.B., Swift, R.S., 2020. Chapter One - Vindication of humic substances as a key component of organic matter in soil and water, in: Sparks, D.L. (Ed.), Advances in Agronomy. Academic Press, pp. 1–37. https://doi.org/https://doi.org/10.1016/bs.agron.2020.05.001

Jacobsen, O.H., Moldrup, P., Larsen, C., Konnerup, L., Petersen, L.W., 1997. Particle transport in macropores of undisturbed soil columns. J. Hydrol. 196, 185–203. https://doi.org/10.1016/S0022-1694(96)03291-X

Jie, C., Jing-zhang, C., Man-zhi, T., Zi-tong, G., 2002. Soil degradation: a global problem endangering sustainable development. J. Geogr. Sci. 12, 243–252. https://doi.org/10.1007/bf02837480

Luo, Z., Wang, G., Wang, E., 2019. Global subsoil organic carbon turnover times dominantly controlled by soil properties rather than climate. Nat. Commun. 10, 1–10. https://doi.org/10.1038/s41467-019-11597-9

McLauchlan, K. The Nature and Longevity of Agricultural Impacts on Soil Carbon and Nutrients: A Review. Ecosystems 9, 1364–1382 (2006). https://doi.org/10.1007/s10021-005-0135-1

Plaza C, Giannetta B, Benavente I, Vischetti C, Zaccone C. Density-based fractionation of soil organic matter: effects of heavy liquid and heavy fraction washing. Sci Rep. 2019 Jul 12;9(1):10146. doi: 10.1038/s41598-019-46577-y. PMID: 31300692; PMCID: PMC6626057.

Pereira, P., Bogunovic, I., Muñoz-Rojas, M., Brevik, E.C., 2018. Soil ecosystem services, sustainability, valuation and management. Curr. Opin. Environ. Sci. Heal. 5, 7–13. https://doi.org/10.1016/j.coesh.2017.12.003

Sun, S., Li, Z., Wang, R., Zhang, J., Pan, C., Cai, Z., 2019. Conversion of secondary forests into chestnut forests affects soil nutrients in Anji County, China. Sustain. 11, 1–14. https://doi.org/10.3390/su11082373

Venanzi, R., Picchio, R., Piovesan, G., 2016. Silvicultural and logging impact on soil characteristics in Chestnut (Castanea sativa Mill.) Mediterranean coppice. Ecol. Eng. 92, 82–89. https://doi.org/https://doi.org/10.1016/j.ecoleng.2016.03.034

Wang, Fang, Harindintwali, J.D., Yuan, Zhizhang, Wang, M., Wang, Faming, Li, S., Yin, Z., Huang, L., Fu, Y., Li, L., Chang, S.X., Zhang, L., Rinklebe, J., Yuan, Zuoqiang, Zhu, Q., Xiang, L., Tsang, D.C.W., Xu, L., Jiang, X., Liu, J., Wei, N., Kästner, M., Zou, Y., Ok, Y.S., Shen, J., Peng, D., Zhang, W., Barceló, D., Zhou, Y., Bai, Z., Li, B., Zhang, B., Wei, K., Cao, H., Tan, Z., Zhao, L. bin, He, X., Zheng, J., Bolan, N., Liu, X., Huang, C., Dietmann, S., Luo, M., Sun, N., Gong, J., Gong, Y., Brahushi, F., Zhang, T., Xiao, C., Li, X., Chen, W., Jiao, N., Lehmann, J., Zhu, Y.G., Jin, H., Schäffer, A., Tiedje, J.M., Chen, J.M., 2021. Technologies and perspectives for achieving carbon neutrality. Innov. 2. https://doi.org/10.1016/j.xinn.2021.100180

Appendix – Supplementary data

Table S1 - First year general features of each plot and morphology of the soil profiles under *Castanea sativa* L. Monte San Savino, Pievebovigliana, Marche, Italy. For symbols see legend.

Mean annual air temperature and rainfall in 1991-2010 period: mean annual total precipitation, 945 mm; mean annual air temperature, 13°C.

Horizon[a]	Depth cm	Thickness cm	Bundary[b]	Color[c]	Skeleton % at sight	Structure[d]	Consistency[e]	Roots[f]	Other observations
Profile n° 1 (43° 4' 6.121" N, 13° 6' 35.445" E WGS84). Altitude: 820 m; Bed rock: Sandstone interbedded with siltstone layers. Slope: 38%; Exposure: N-NO. Management: not pruductive chestnut forest in conversion to marroni plantation. Vegetation – Trees: *Ostrya carpinifolia* L., *Populus tremula* L. Bushes: *Rubus ulmifolius* L., *Crataegus monogyna* L.; Herbaceous layer: *Ciclamen spp*.; Soil: Typic Dystrustept (Soil Survey Staff, 2014).									
OLn	4.5-1.5	2-6	C, W	-	-	-	-	-	Leaves, brances, urchins and chestnuts
OLv	1.5-1	0.5-1	C, W	-	-	-	-	-	-
OF+OH	1-0	1-2	A, W	-	-	2, sbk, gr, f	fr	2, vf,1, f	Sporadic millimetric A horizon
Bw1	0-16	12-20	C, W	10YR 4/6	-	2-3, sbk, m, co	fr	1, vf, 2, f, 3, m, co	Lessivage salt-and-pepper effect on aggregates, mottles 5%
Bw2	16-41	20-26	C, W	10YR 4/6	-	2, sbk, co, m	fr	1, vf, f, 2, m, co	Mottles 15%, cutans, dead roots channels
Bw3	41-66	18-32	C, W	10YR 5/6	-	2, sbk, co, m	fr	1, vf, f, 2, m, co	Charcoal fragments, mottles 20-25%
Bg	66-96	28-32	C, W	10YR 5/6	-	2, sbk, co, m	fr	1, vf, f, 2, m, co	Mottles, Fe-Mn nodules-
C	96+	-	-	-	-	-	-	-	-
Profile n° 2 (43° 4' 6.236"N, 13° 6' 35.395"' E WGS84). Altitude: 820 m; Bed rock: Sandstone interbedded with siltstone layers. Slope: 42%; Exposure: N-NO. Management: not pruductive chestnut forest in conversion to marroni plantation. Vegetation – Trees: *Ostrya carpinifolia* L., *Populus tremula* L. Bushes: *Rubus ulmifolius* L., *Crataegus monogyna* L.; Herbaceous layer: *Ciclamen spp*.; Soil: Typic Dystrustept (Soil Survey Staff, 2014).									
OLn	7-3	3-8	C, W	-	-	-	-	-	Leaves, brances, urchins and chestnuts
OLv	3-1	2-3	C, W	-	-	-	-	-	Mycelium
OF+OH	1-0	1-2	A, W	-	-	2, sbk, gr, f	fr	2, vf,1, f	Mesofauna
A	0-1	-	-	10YR 2/1	-	2 gr, f, m	fr	2 vf, f	-
Bw1	1-14	10-15	C, W	10YR 4/6	-	3-2 sbk, m, co	fr	1, vf, m, co, 3, f	Mycelium, roots channels, lessivage morphologies
Bw2	14-40	25-28	C, W	10YR 4/6	-	2 sbk, abk, m, co	fr	1, vf, 3, f, m, co	Lessivage salt-and-pepper effect on aggregates, cutans, mottles 5%, vole tubes
Bw3	40-55	13-17	C, W	10YR 5/6	-	2 sbk, abk, m, co	fr	1, vf, 3, f, m, co	Charcoal fragments, mottles 15%

Bg	55-93	14-24	C, W	10YR 5/6	-	2 sbk, abk, m, co	fr	1, vf, 3, f, m, co	Mottles
C	93+	-	-	-	-	-	-	-	-
Profile n° 3 (43° 4' 6.629"N, 13° 6' 34.905" E WGS84). Altitude: 820 m; Bed rock: Sandstone interbedded with siltstone layers. Slope: 35%; Exposure: N-NO. Management: not pruductive chestnut forest in conversion to marroni plantation. Vegetation – Trees: *Ostrya carpinifolia* L., *Populus tremula* L. Bushes: *Rubus ulmifolius* L., *Crataegus monogyna* L.; Herbaceous layer: *Ciclamen spp*.; Soil: Typic Dystrustept (Soil Survey Staff, 2014).									
OLn	6-2	2-8	C, W	-	-	-	-	-	Leaves, brances, urchins and chestnuts
OLv	2-1	1-2	C, W	-	-	-	-	-	-
OF+OH	1-0	0.5-1	C, W	-	-	2, sbk, gr, f	fr	2, vf,1, f	Mesofauna
AB	0-5	3-6	C, W	10YR 3/2	-	2, abk, m, f	fr	2, vf, f	Mesofauna
Bw1	5-14	8-12	C, W	10YR 4/6	-	2, sbk, abk, co, m	fr	1, vf, 2, f	Charcoal fragments, lessivage salt-and-pepper effect on aggregates, cutans.
Bw2	14-36	20-24	C, W	10YR 4/6	-	2, sbk, abk, co, m	fr	1, vf, 2, f, 3, co, m	Charcoal fragments, lessivage salt-and-pepper effect on aggregates, cutans.
Bw3	36-59	17-29	C, W	2.5Y 5/6	-	2, sbk, abk, co, m	fr	1, vf, 2, f, 3, co, m	Mottles 10%, cutans, charcoal fragments
Bg	59-115	50-62	C, W	2.5Y 5/6	-	2, sbk, abk, co, m	fr	1, vf, 2, f, 3, co, m	Mottles, charcoal fragments
C	115+	-	-	-	-	-	-	-	-
Profile n° 6 (43° 4' 9.264"N, 13° 6' 41.911" E WGS84). Altitude: 820 m; Bed rock: Sandstone interbedded with siltstone layers. Slope: 40%; Exposure: N-NO. Management: not pruductive chestnut forest. Vegetation – Trees: *Ostrya carpinifolia* L., *Populus tremula* L. Bushes: *Rubus ulmifolius* L., *Crataegus monogyna* L.; Herbaceous layer: *Ciclamen spp*.; Soil: Typic Dystrustept (Soil Survey Staff, 2014).									
OLn	8-2	5-11	C, W	-	-	-	-	-	Leaves, branches, urchins and chestnuts, hazelnuts shells
OLv	2-1.5	-	B	-	-	-	-	-	leaves, branches, urchins and chestnuts, hazelnuts shells; mesofauna; few mycelium
OF+OH	1.5-0	-	C, W	-	-	2, sbk, gr, f	fr	2, vf,1, f	Mesofauna; few mycelium
AB1	0-2	1-2	C, W	2.5Y 3/3	-	2-3, sbk, m, f	fr	3, vf, 2, f	Mesofauna
AB2	2-9	4-8	C, W	2.5Y 3/3	-	2, sbk, m, f	fr	3, vf, 2, f	Roots channels
Bw1	9-16	6-8	C, W	10YR 4/6	-	2, sbk, abk, f, m, co	fr	1, vf, co, 2, f, m	Few mottles, cutans, roots channels
Bw2	16-34	17-20	C, W	10YR 4/6	-	2-3, sbk, abk, f, m	fr	1, vf, 2, f, 3, co, m	Charcoal fragments, lessivage salt-and-pepper effect on aggregates, cutans, Mn hydroxides
Bw3	34-54	20-23	C, W	10YR 4/6	-	2, sbk, abk, co, m	fr	1, vf, 2, f, 3, co, m	Mottles 15%, cutans, few charcoal fragments
Bg1	54-90	32-36	C, W	10YR 5/8	-	2, sbk, abk, co,	fr	1, vf, f	Mottles, Mn hydroxides

						m			
Bg2	90-106+	-	-	10YR 5/8	-	2, sbk, abk, co, m	fr	1, vf, f	Mottles

Profile n° 7 (43° 4' 10.081" N, 13° 6' 41.619" E WGS84). Altitude: 820 m; Bed rock: Sandstone interbedded with siltstone layers.
Slope: 45%; Exposure: N-NO. Management: not pruductive chestnut forest. Vegetation – Trees: *Ostrya carpinifolia* L., *Populus tremula* L. Bushes: *Rubus ulmifolius* L., *Crataegus monogyna* L.*;* Herbaceous layer: *Ciclamen spp*.; Soil: Typic Dystrustept (Soil Survey Staff, 2014).

OLn	4.5-1.5	2-6	C, W	-	-	-	-	-	Leaves, branches, urchins and chestnuts
OLv	1.5-1	-	B	-	-	-	-	-	Mesofauna, roots channels
OF+OH	1-0	0.5-1	C, W	-	-	2, gr, f	fr	2, vf,1, f	Mesofauna
AB	0-2	1-3	C, W	10YR 1/2	-	2, sbk, f	fr	2, vf, 1, f, m	Mesofauna
Bw1	2-17	8-15	C, W	10YR 4/6	-	3, sbk, abk, co, m, f	fr	2, vf, m, co 3, f	Charcoal fragments, lessivage salt-and-pepper effect on aggregates, cutans, Mn hydroxides
Bw2	17-22	4-6	C, W	10YR 4/6	-	2-3, sbk, abk, f, m	fr	1, vf, 2, f, co, m	Charcoal fragments, lessivage salt-and-pepper effect on aggregates, cutans, Mn hydroxides
Bw3	22-35	10-15	C, W	10YR 4/6	-	2-3, sbk, co, m, f	fr	1, vf, 2, f, co, m	Cutans
Bw4	35-54	17-21	C, W	10YR 4/6	-	2, sbk, co, m	fr	1, vf, 2, f, 3, co, m	Mottles 15%, mycelium, dead roots
Bg1	54-76	20-24	C, W	10YR 5/6	-	2, sbk, co, m	fr	1, vf, 2, f, 3, co, m	Mottles, Mn hydroxides
Bg2	76-106	27-33	C, W	10YR 5/6	-	2, sbk, co, m	fr	1, vf, 2, f, 3, co, m	Mottles, Mn hydroxides
C	106+	-	-	-	-	-	-	-	-

Profile n° 8 (43° 4' 10.261" N, 13° 6' 41.05" E WGS84). Altitude: 800 m; Bed rock: Sandstone interbedded with siltstone layers.
Slope: 38%; Exposure: N-NO. Management: not pruductive chestnut forest. Vegetation – Trees: *Ostrya carpinifolia L.*, *Populus tremula L.* Bushes: *Rubus ulmifolius L.*, *Crataegus monogyna L.;* Herbaceous layer: *Ciclamen spp*.; Soil: Typic Dystrustept (Soil Survey Staff, 2014).

OLn	5.5-1.5	5-11	C, W	-	-	-	-	-	Leaves, branches, urchins and chestnuts
OLv	1.5-1	0.5-1	C, W	-	-	-	-	-	Mesofauna, mycelium
OF+OH	1-0	1-2	C, W	-	-	3, gr, f	fr	3, vf	Mesofauna, mycelium
A	0-2	2-6	C, W	10YR 2/1	-	2, sbk, m, f, gr, m, f	fr	3, vf, f	-
Bw1	2-9	6-9	C, W	10YR 5/6	-	2, sbk, abk, co, m	fr	1, vf, 3, f, m	-
Bw2	9-24	11-16	C, W	10YR 4/6	-	2, sbk, abk, co, m	fr	1, vf, 3, co, m, f	Roots channels filled with organic matter colonized by fungal hyphae
Bw3	24-95	68-73	C, W	10YR 4/6	-	2, sbk, co, m, f	fr	1, vf, 2, f, 3, co, m	Mottles 10%, Fe/Mn hydroxides
Bg	95-120	22-28	C, W	2.5Y 6/6	-	2, sbk, co, m, f	fr	1, vf, 2, f, 3, co, m	Mottles 15%, Fe/Mn hydroxides
C	120+	-	-	-	-	-	-	-	-

Profile n° 9 (43° 4' 8.728" N, 13° 6' 32.162" E WGS84). Altitude: 820 m; Bed rock: Sandstone interbedded with siltstone layers
Slope: 10%; Exposure: N-NO. Management: Marroni groove. Vegetation – Trees: *Ostrya carpinifolia L., Populus tremula L.* Bushes: *Rubus ulmifolius L., Crataegus monogyna L.;* Herbaceous layer: *Ciclamen spp*.; Soil: Typic Dystrustept (Soil Survey Staff, 2014).

OLn	5.5-0.5	4-12	C, W	-	-	-	-	-	Leaves, branches, urchins and chestnuts
OLv	0.5-0	-	A, B	-	-	-	-	-	Leaves, branches, urchins and chestnuts, mycelium and earthworms
AB	0-7	5-9	C, W	2.5Y 3/3	-	3, sbk, co, m, gr, f	fr	2, vf, 1, f	earthworms
AB&B	7-17	8-12	C, W	10YR 4/6	-	3, sbk, m, f	fr	2, vf, 1, f	Mycelium earthworms
Bw	17-30	12-14	C, W	10YR 4/6	-	2, sbk, co, m	fr	1, vf, 2, f, 3, m	Broken A horizon, mycelium, mottles 10%
Ab	30-41	9-12	C, W	10YR 3/6	-	1, sbk, m, f	fr	2, vf, f,	Cutans
Bwb1	41-54	50-62	C, W	2.5Y 5/6	-	2, sbk, co, m	fr	1, vf, 2, f, 3, co, m	Fe/Mn hydroxides
Bwb2	54-100+	-	-	2.5Y 5/6	-	2, sbk, co, m	fr	1, vf, 2, f, 3, co, m	Fe/Mn hydroxides

Profile n° 10 (43° 4' 9.177" N, 13° 6' 31.37" E WGS84). Altitudine: 820 m Bed rock: Sandstone interbedded with siltstone layers
Slope: 55%; Exposure: N-NO. Management: Marroni groove. Vegetation – Trees: *Ostrya carpinifolia L., Populus tremula L.* Bushes: *Rubus ulmifolius L., Crataegus monogyna L.;* Herbaceous layer: *Ciclamen spp*.; Soil: Typic Dystrustept (Soil Survey Staff, 2014).

OLn	6-1	4-9	C, W	-	-	-	-	-	Leaves, branches, urchins and chestnuts
OLv	0.5-0	1-2	B	-	-	-	-	-	-
OF+OH	1-0/0.5-1	0.5-1	C, W	-	-	2, sbk, gr, f	fr	2, vf,1, f	Mesofauna
AB&B	0-16	14-26	C, I	10YR 3/4	-	2-3, sbk, m, f	fr	3, vf, f, 1, co, m	Mycelium, mesofauna
Ab	16-26	8-12	A, B	10YR 3/4	-	2, sbk, m, f	fr	3, vf, f, 1 co, m	-
Bwb1	26-41	10-25	C, I	10YR 4/6	-	2, sbk, abk, co, m	fr	1, co, m, f, vf	Fe/Mn hydroxides (15%), Roots channels filled with organic matter
Bwb2	41-81+	30-50	-	10YR 3/6	-	2, sbk, abk, co, m	fr	1, co, m, f, vf	Fe/Mn hydroxides (15%)

Profile n° 11 (43° 4' 10.041" N, 13° 6' 29.577" E WGS84). Altitudine: 820 m; Bed rock: Sandstone interbedded with siltstone layers
Slope: 20%; Exposure: N-NO. Management: Marroni groove. Vegetation – Trees: *Ostrya carpinifolia L., Populus tremula L.* Bushes: *Rubus ulmifolius L., Crataegus monogyna L.;* Herbaceous layer: *Ciclamen spp*.; Soil: Typic Dystrustept (Soil Survey Staff, 2014).

OLn	7-1	5-10	C, W	-	-	-	-	-	Leaves, branches, urchins and chestnuts
OLv	-	0.5	B	-	-	-	-	-	-
OF+OH	1-0	1-1.5	C, W	-	-	2, sbk, gr, f	fr	2, vf,1, f	Mesofauna
AB	0-5	3-6	C, W	2.5Y 3/3	-	2-3, sbk, m, f	fr	3, vf, 1, f	-
Bw1	5-20	15-16	C, W	10YR 5/8	-	2-3, sbk, co, m, f	fr	2, vf, f, 1, co, m	-
Bw2	20-34	12-16	C, W	10YR 4/6	-	2-3, sbk, abk, co, m	fr	2, vf, 3, co, m, f	-

Bw3	34-53	17-29	C, W	10YR 4/6	-	2-3, sbk, co, m, f	fr	1, co, m, vf, 3, f,	Fe/Mn hydroxides (5%)
Bw4	53-73	50-62	C, W	10YR 3/6	-	2-3, sbk, co, m, f	fr	1, vf, 2, f, 3, co, m	Fe/Mn hydroxides (20%)
Bw5	73-108+	-	-	10YR 3/6	-	2-3, sbk, co, m, f	fr	1, vf, 2, f, 3, co, m	Fe/Mn hydroxides (20%)

[a]Horizons: designation according to Baize et al. (2008) for organic horizons, to Schoeneberger et al. (2012) for mineral horizons..

[b]C=clear; G=gradual; D=diffuse; S=smooth; W=weavy; I=irregular; B=broken

[c] Field humidity Munsell Soil Color Charts.

[d] 1=weak, 2=moderate, 3=strong; f=fine, m=medium, c=coarse; gr=granular, abk=angular blocky, sbk=sub-angular blocky; fi=firm; m= moist; fr=friable; vfr=very friable; w=wet; ss=slightly sticky.

[e] fr, friable

[f] 0=absent, v_1=very few, 1=few, 2=plentiful, 3=abundant; mi=micro, vf=very fine, f=fine, m=medium, co=coarse.

Table S2 - Second year general features of each plot and morphology of the soil profiles under *Castanea sativa* L. Monte San Savino, Pievebovigliana, Marche, Italy. For symbols see legend.

Mean annual air temperature and rainfall in 1991-2010 period: mean annual total precipitation, 945 mm; mean annual air temperature, 13°C.

Horizon[a]	Depth cm	Thickness cm	Bundary[b]	Color[c]	Skeleton % at sight	Structure[d]	Consistency[e]	Roots[f]	Other observations
Profile n° 1 (43° 4' 6.121" N, 13° 6' 35.445" E WGS84). Altitude: 820 m; Bed rock: Sandstone interbedded with siltstone layers. Slope: 38%; Exposure: N-NO. Management: not pruductive chestnut forest in conversion to marroni plantation. Vegetation – Trees: *Castanea sativa* Mill., *Corylus avellana* L., *Acer opalus obtusatum* (Waldst & Kit. Ex Wild.) Gams, *Fagus sylvatica* L., *Populus tremula* L. Bushes *Rubus ulmifolius* L., *Rosa canina* L.; Herbaceous layer: -; Soil: Typic Dystrustept (Soil Survey Staff, 2014).									
OLn	0-1	0.5-1.5	C, W	-	-	-	-	-	Leaves, branches, urchins and chestnuts
OLv	1-3	0.5-4	C, W	-	-	-	-	-	Partly degraded leaves, branches, urchins and chestnuts
OF+OH	3-7	2-7	C, W	-	-	-	-	-	Fungal hyphae
AB	7-12	3-7	C, W	7.5YR 3/2	-	1-2, sbk, vf, f, m	fr	2, vf, 3, f	-

Bw	12-47+	-	-	7.5YR 5/3	-	1-2, abk, vf, f, m	fr	2, vf, f	-

Profile n° 2 (43° 4' 6.236"N, 13° 6' 35.395"' E WGS84). Altitude: 820 m; Bed rock: Sandstone interbedded with siltstone layers.
Slope: 42%; Exposure: N-NO. Management: not pruductive chestnut forest in conversion to marroni plantation. Vegetation – Trees: *Castanea sativa* Mill., *Corylus avellana* L., *Acer opalus obtusatum* (Waldst & Kit. Ex Wild.) Gams, *Fagus sylvatica* L., *Populus tremula* L. Bushes *Rubus ulmifolius* L., *Rosa canina* L.*;* Herbaceous layer: -; Soil: Typic Dystrustept (Soil Survey Staff, 2014).

OLn	0-2	0-2	C, W	-	-	-	-	-	Leaves, branches, urchins and chestnuts
OLv	2-4	1-3	C, W	-	-	-	-	-	Partly degraded leaves, branches, urchins and chestnuts, mycelium
OF+OH	4-6	1-3	C, W	-	-	-	-	-	Fungal hyphae
AB	6-9	4-5	C, W	10YR 3/2	-	1 sbk f, m, co vco	fr	3 vf, f	-
Bw1	9-24	14-16	C, W	10YR 5/4	-	3 sbk, m, co	fr	3, vf, m	-
Bw2	24-37	11-14	C, W	10YR 4/6	-	3 sbk , vf, f, m	fr	3, vf, 1, m,	-
Bw3	37-43+	-	-	-	-	-	-	-	-

Profile n° 3 (43° 4' 6.629"N, 13° 6' 34.905" E WGS84). Altitude: 820 m; Bed rock: Sandstone interbedded with siltstone layers.
Slope: 35%; Exposure: N-NO. Management: not pruductive chestnut forest in conversion to marroni plantation. Vegetation – Trees: *Castanea sativa* Mill., *Corylus avellana* L., *Acer opalus obtusatum* (Waldst & Kit. Ex Wild.) Gams, *Fagus sylvatica* L., *Populus tremula* L. Bushes *Rubus ulmifolius* L., *Rosa canina* L.*;* Herbaceous layer: -; Soil: Typic Dystrustept (Soil Survey Staff, 2014).

OLn	0-1	0.5-1.5	C, W	-	-	-	-	-	Leaves, branches, urchins and chestnuts
OLv	1-4	2-4	C, W	-	-	-	-	-	Partly degraded leaves, branches, urchins and chestnuts
OF+OH	4-6	1-4	C, W	-	-	-	-	-	Fungal hyphae
AB	6-12	3-5	C, W	10YR 5/6	-	3, sbk, vf, f, m, co	fr	2, vf, f	-
Bw1	12-33	14-24	C, W	10YR 4/3	-	3, sbk, vf, f, m, co	fr	2, vf, f	-
Bw2	33-48+	-	-	10YR 5/6	-	3, sbk, vf, f, m, co	fr	2, vf, f, 1 m	-

Profile n° 6 (43° 4' 9.264"N, 13° 6' 41.911" E WGS84). Altitude: 800 m; Bed rock: Sandstone interbedded with siltstone layers.
Slope: 40%; Exposure: N-NO. Management: not pruductive chestnut forest. Vegetation – Trees: *Corylus avellana* L., *Populus tremula* L., *Quercus pubescens* L.; Bushes: *Rubus ulmifolius* L.*;* Herbaceous layer: -; Soil: Typic Dystrustept (Soil Survey Staff, 2014).

OLn	0-3	1-5	C, W	-	-	-	-	-	Leaves, branches, urchins, chestnuts and hazelnut shells
Olv+OF	3-4	0.5-1.5	A, W	-	-	-	-	-	Leaves, branches, urchins, chestnuts and hazelnut shells
AB	4-9	4-6	C, W	7.5YR 3/2	-	3, sbk, vf, f, m	fr	3, vf, f, 2, m	Roots residues

Bw1	9-24	11-15	C, W	10YR 4/6	-	3, sbk, vf, f, m, co	fr	3, vf, m	-
Bw2	24-37	11-13	C, W	10YR 5/8	-	3, sbk, vf, f, m, co	fr	3, f, m 1, co	-
Bw3	37-44+	-	-	10YR 5/6	-	3, sbk, mf, m	fr	1, f, m	Mn nodules
Profile n° 7 (43° 4' 10.081" N, 13° 6' 41.619" E WGS84). Altitude: 800 m; Bed rock: Sandstone interbedded with siltstone layers. Slope: 45%; Exposure: N-NO. Management: not pruductive chestnut forest. Vegetation – Trees: *Acer opalus obtusatum* (Waldst & Kit. Ex Wild.) Gams, *Castanea sativa* Mill.,., *Corylus avellana* L., *Fagus sylvatica* L., *Ostrya carpinifolia* L.; Bushes: *Rubus ulmifolius* L., *Crataegus monogyna* L.; Herbaceous layer: -; Soil: Typic Dystrustept (Soil Survey Staff, 2014).									
OLn	0-2	1-3	C, W	-	-	-	-	-	Leaves, branches, urchins and chestnuts
OLv+OF	2-4	1-3	C, W	-	-	-	-	-	Leaves, branches, urchins, chestnuts and beechnuts, abundant hyphae
Bw+OH	4-8	0-3	A, W	10YR4/4 10YR 4/2	-	3, gr, f, sbk, vf, f, m, co	fr	3, vf, f	Fungal hyphae
AB	8-15	3-8	C, W	10YR 3/2	-	3, sbk, vf, f	fr	3, vf, f, m, 1, co	Fungal hyphae
Bw	15-44+	-	-	10YR 4/6	-	3, sbk, vf, f, m, co	fr	3, vf, f, 1,m	Degraded organic matter, degraded roots, Mn nodules
Profile n° 8 (43° 4' 10.261" N, 13° 6' 41.05" E WGS84). Altitude: 800 m; Bed rock: Sandstone interbedded with siltstone layers. Slope: 38%; Exposure: N-NO. Management: not pruductive chestnut forest. Vegetation – Trees: *Acer opalus obtusatum* (Waldst & Kit. Ex Wild.) Gams, *Castanea sativa* Mill., *Corylus avellana* L., *Fagus sylvatica* L., *Ostrya carpinifolia* L.; Bushes: *Rubus ulmifolius* L., *Crataegus monogyna* L.; Herbaceous layer: -; Soil: Typic Dystrustept (Soil Survey Staff, 2014).									
OLn	0-3	1.5-4.5	C, W	-	-	-	-	-	Leaves, branches and urchins
OLv+OF	3-5	1-3	A, W	-	-	-	-	-	Leaves, branches and urchins
AB	5-9	4-6	C, W	10YR 2/1	-	3, sbk, vf, f	fr	2, vf, f, 3, m	-
Bw1	9-21	10-12	C, W	10YR 4/4	-	3, sbk, vf, f, m	fr	2, f, m	-
Bw2	21-34	12-14	C, W	10YR 4/4	-	3, sbk, vf, f, m	fr	3, vf, f, 1, m	-
Bw3	34-44+	-	-	10YR 5/8	-	3, sbk, vf, f, m	(w)ps	1, vf, f, m	-
Profile n° 9 (43° 4' 8.728" N, 13° 6' 32.162" E WGS84) Altitude: 820 m; Bed rock: Sandstone interbedded with siltstone layers. Slope: 10%; Exposure: N-NO. Management: Marroni groove. Vegetation – Trees: *Acer opalus obtusatum* (Waldst & Kit. Ex Wild.) Gams, *Castanea sativa* Mill., *Corylus avellana* L., *Sorbus torminalis* L., *Sorbus aucuparia* L.; Bushes: *Rubus ulmifolius* L., *Rosa canina* L.; Herbaceous layer: *Fragaria vesca* L, *Hippocrepis* spp., *Matricaria chamomilla* L., *Pteridium aquilinum* L; Soil: Typic Dystrustept (Soil Survey Staff, 2014).									
OLn	0-2	1-3	C, W	-	-	-	-	-	Leaves, branches, urchins and chestnuts
OLv	2-5	2-4	C, W	-	-	-	-	-	Leaves, branches, urchins, chestnuts and hyphae
OF+OH	5-7	1-2	A, S	-	-	-	-	-	Hyphae, earthworms and animal nest
Bw1	7-21	10-18	C, W	10YR 4/6	-	2-3, sbk, vf, f, m	fr	1, vf, 2, m	hyphae, abundant Mn nodules
Bw2	21-44	16-20	C, W	10YR 4/6	-	3, sbk, vf, f, m	fr	1, vf, 3, f, m	hyphae, scarce Mn nodules
Bw3	44-48+	-	-	-	-	-	-	-	-
Profile n° 10 (43° 4' 9.177" N, 13° 6' 31.37" E WGS84) Altitude: 820 m; Bed rock: Sandstone interbedded with siltstone layers.									

Slope: 15%; Exposure: N-NO. Management: Marroni groove. Vegetation – Trees: *Acer opalus obtusatum* (Waldst & Kit. Ex Wild.) Gams, *Castanea sativa* Mill., *Corylus avellana* L., *Sorbus torminalis* L., *Sorbus aucuparia* L.*;* Bushes: *Rubus ulmifolius* L.*, Rosa canina* L.*;* Herbaceous layer: *Fragaria vesca* L, *Hippocrepis* spp., *Matricaria chamomilla* L., *Pteridium aquilinum* L*;* Soil: Typic Dystrustept (Soil Survey Staff, 2014).									
OLn	0-2	1-3	C, W	-	-	-	-	-	Leaves, branches, urchins and chestnuts
OLv	2-5	2-4	C, W	-	-	-	-	-	Leaves, branches, urchins, chestnuts and hyphae
OF+OH	5-7	-	A, S	-	-	-	-	-	Hyphae and mesofauna
Bw1	7-19	10-12	C, W	10YR 4/6	-	2-3, sbk, vf, f, m	vfr	3, vf, 2, m	-
Bw2	19-45	24-25	C, W	10YR 4/6	-	3, sbk, vf, f, m	vfr	1, vf, f, m	-
Bw3	45-47+	-	-	-	-	-	-	-	-
Profile n° 11 (43° 4' 10.041" N, 13° 6' 29.577" E WGS84). Altitude: 820 m; Bed rock: Sandstone interbedded with siltstone layers. Slope: 20%; Exposure: N-NO. Management: Marroni groove. Vegetation – Trees: *Acer opalus obtusatum* (Waldst & Kit. Ex Wild.) Gams, *Castanea sativa* Mill., *Corylus avellana* L., *Sorbus torminalis* L., *Sorbus aucuparia* L.*;* Bushes: *Rubus ulmifolius* L.*, Rosa canina* L.*;* Herbaceous layer: *Fragaria vesca* L, *Hippocrepis* spp., *Matricaria chamomilla* L., *Pteridium aquilinum* L*;* Soil: Typic Dystrustept (Soil Survey Staff, 2014).									
OLn	0-1	0.5-1.5	C, W	-	-	-	-	-	Leaves, branches, urchins and chestnuts
OLv	-	0.5	B	-	-	-	-	-	-
AB	1-4	3-4	C, W	10YR 4/4	-	3, sbk, vf, f	fr	3, vf	Hyphae, mesofauna
Bw1	4-11	6-8	C, W	10YR 5/6	-	3, sbk, vf, f, m	fr	3, f	-
Bw2	11-27	13-14	C, W	10YR 5/6	-	3, sbk, vf, f, m	fr	3vf, f, 2, m	Charcoal fragments (2%)
Bw3	27-39+	-	C, W	10YR 5/8	-	3, sbk, vf, f, m	fr	3, vf, f, 1 vco	Mn nodules

[a] Horizons: designation according to Baize et al. (2008) for organic horizons, to Schoeneberger et al. (2012) for mineral horizons.

[b]C=clear; G=gradual; D=diffuse; S=smooth; W=weavy; I=irregular; B=broken

[c] Field humidity Munsell Soil Color Charts.

[d] 1=weak, 2=moderate, 3=strong; f=fine, m=medium, c=coarse; gr=granular, abk=angular blocky, sbk=sub-angular blocky; fi=firm; m= moist; fr=friable; vfr=very friable; w=wet; ss=slightly sticky.

[e] fr=friable; vfr=very friable

[f] 0=absent, v_1=very few, 1=few, 2=plentiful, 3=abundant; mi=micro, vf=very fine, f=fine, m=medium, co=coarse.

CHAPTER 6 - FINAL CONSIDERATIONS

Forest ecosystems cover ≈ $4 \cdot 10^9$ ha of landmass that represent on average 31% of Earth surface and provide precious resources for ≈$1.6 \cdot 10^9$ of human beings (included indigenous populations). Forests are fundamental not only for human subsistence purpose in terms of materials (e.g. timber, food, medicines, and water), but also for the ecosystems services and the contribution to soil formation and maintenance. Forest soils are the most biologically rich habitats and the biggest reservoir of C and nutrients like N and P of the Earth having a predominant role in all biogeochemical cycles. Following the destiny of the coenoses that grow over it, soil is impacted by the effects of different managements. In particular, land use changes (LUC) can have negative, neutral, or positive effects on forest soils depending on the intervention type and intensity.

The aim of this thesis was therefore to assess the impact of LUC on soil capacity to store organic C and other nutrients (N, P, Ca, Mg and K) in forest ecosystems and the results can be resumed as follows:

1. The soil stock of C and nutrients in the litter and in the 0-30, 30-50, and 50-75 cm layers under a multi-millennial Turkey oak forest cover, appeared to be slightly influenced by thinnings operated in the last 70 years of management. The only parameters that appeared to be more affected by thinning were available P and exchangeable Mg. The more intense thinning was able to increase the 1-cm storage of the organo-mineral horizons via a major SOM mineralization. Basically, in three millennia of Turkey oak forest use, forest cover and human activity are the main soil forming forces.
2. The stocks of organic C and nutrients in the soils under long-time coppice-managed Holm oak forests were little influenced by parent materials. This depends on the long-time during which plants have modified the soil properties trough acidification, mineral weathering, SOM addition, and biocycling of nutrients. These behaviours have reduced the influence of the parent materials on the soil properties making them similar in soils derived from different lithologies, especially in the upper horizons. However, some differences did occur because of the lithology, as the influence of

the calcareous parent material on the amount of available Ca in the mineral horizons and in both fine earth and skeletal fraction.

3. Organic C stock in aboveground biomass, litter, mineral soil, and roots within a depth of 30 cm in Apennines broadleaves forests subjected to a differentiate management is influenced by three elements: plant-site relation, stand biological characteristics, and management practices. In particular, the past management (testified by human manufacts as charcoal kilns) seems to have a predominant role in conditioning the soil and plants organic C stock in this complex forest ecosystems that show a high interdependence with human activities.

4. The two years monitoring activity conducted in an Apennines chestnut forest subjected to a differentiated management on the total and fractionated organic C stock of the 0-30 cm soil depth-layer showed a strict connection between the coenoses, the site features, the soil properties, and the management with evidence for texture and mineralogy, soil reaction, TOC, WEOC, and MAOC amounts. TOC and fractionated organic C stock in 0-30 cm depth-layer reveal differences from the first to the second year that seem to be dependent on site-specific features to be investigated more in depth.