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GIS-Based Geopedological Approach for Assessing Land Suitability for Chestnut (*Castanea sativa* Mill.) Groves for Fruit Production

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Abstract: The identification of mountainous areas suitable for chestnut stands for fruit production (CSFP) is raising increasing interest among researchers. This work aimed to (*i*) identify the areas suitable for CSFP shown in a land suitability map easy to read by land planners, and (*ii*) propose a remote-sensing-based methodology able to identify the lands currently under cultivation for CSFP. This study was conducted using the QGIS software for the Municipality of Castel del Rio, Emilia-Romagna Region, Italy. To obtain the land suitability map, topographic, lithological, and pedological data were acquired, and the areas located between 200 and 1000 m of altitude, with north exposition, a slope < 20°, sandstone-based lithology, and soils with dystric features were selected. The currently cultivated areas for CSFP were identified through remote-sensing images of the early spring period, which were delineated and georeferenced. The findings showed that only 10% of the whole study site area can be considered suitable for CSFP. Further, most of the currently cultivated CSFP (59%) are in non-suitable areas characterised by high slope gradients. The methodology applied in this study can easily provide detailed information about the suitable areas for CSFP and the areas currently cultivated with chestnut, thus allowing accurate land-use planning and land conservation.

Keywords: land suitability map; sandstone; georeferencing; soil suitability; mountainous areas

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1. Introduction

Sweet chestnut (*Castanea sativa* Mill.) is one of the most widespread deciduous tree species in Europe [1]. Such large distribution was attributed to the multipurpose of chestnut stands because they can be used for firewood, timber, and food production for both human and animal feeding [2,3]. In Italy, chestnut stands cover about 800,000 ha [4], 34,273 ha of which is designated for fruit production [5]. Sweet chestnut has significantly influenced the development of Italian mountainous areas, establishing the so-called "civilisation of the chestnut tree" [6]. However, after World War II, rural depopulation due to changing social needs [7], the spread of the chestnut blight (*Chryphonectria parasitica* (Murr.) Barr) and ink (*Phytophthora cambivora* (Petri) Buism.) diseases [8] and the introduction of the Asian Chestnut Gall Wasp (*Dryocosmus kuriphilus* Yasumatsu) promoted chestnut stand abandonment [9].

Due to the increased worldwide demand for chestnut nuts in the last decade [10], linked to their nutritional characteristics [11] and the increasing interest in chestnut wood [12], both the planting of new chestnut stands and the recovery of suitable abandoned chestnut areas is advisable. In this context, land evaluation for identifying the areas suitable for chestnut stands is essential to prevent the loss of ecosystem services and to ensure high chestnut yield. Therefore, land evaluations that include knowledge of soils, lithology, and morphological features have been recognised as an important requirement in the agricultural planning process [13–15] because they ensure both long-term primary production and the optimum and sustainable utilisation of the available land resources [16,17].

The development of a land evaluation model is prioritised for those plant species growing in mountainous areas, such as chestnut, mainly due to the high degradation vulnerability of these areas [18]. In fact, mountain soils are generally defined as poorly developed, skeletal, shallow, acidic, and relatively infertile [19]. Hence, knowing the potential of a mountainous area to sustain plant growth and productivity through the evaluation of their pedoclimatic and morphological characteristics could be considered of pivotal importance for the recovery of mountain agricultural activities [20].

Going back for generations, the evaluation of the inherent characteristics of the land has always involved farmers in developing land-use systems that would be well adapted to the potentials and constraints of their land. Land planning needs tools able to elaborate the information gathered from remote-sensing data with enhanced spatial and temporal resolutions, using instruments capable of processing multiple pieces of information, to avoid subjective errors. Progress in geographical information system (GIS) technologies allows for the processing of a large number of spatial data and the provision of more accurate and accessible information about the land [21]. GIS can perform numerous tasks using both spatial and attribute data. One of the most useful features of GIS is the ability to overlay different layers or maps that are relevant to the same spatial area [22]. In addition, the use of GIS allows for the development of models from which a new thematic map (e.g., land suitability map) can be formed from a set of thematic maps [22]. Therefore, GIS is a powerful tool in spatial decision-making processes for sustainable development in rural areas [23]. In addition, GIS is an effective software for census land uses in both field-scale and remote-sensing approaches [24,25], which could help to reduce the poor accuracy and limited updating of cadastral data concerning land use [26].

Besides powerful tools such as GIS, land evaluation processes require scientific procedures for an objective assessment of the potential and constraints of a given land for agricultural purposes [27]. A scientific system able to provide information about the appropriateness of land to sustain plant growth was developed by the Food and Agriculture Organization (FAO) [28]. Specifically, the FAO developed the term "land suitability", which estimates the fitness of soil and its landscape for the production of a specific agricultural crop [28]. Land suitability assessment and classification are based on the required inputs, such as labour, fertilisers, or irrigation, necessary for specified cultures.

Over time, land evaluation methods have become more sophisticated [29], and with the enhanced availability of large georeferenced datasets and GIS technologies, evaluations have become more accurate and oriented toward specific vegetation types [30–32].

To further support land evaluation processes, remote sensing was largely used by several researchers [33–36]. These authors used the remote-sensing methodology to acquire information about the topography, land use, and the presence of waterbodies and buildings. In terms of land use, several investigations used GlobCover2009 [34], Landsat [36], and Corine Land Cover [37], but evaluations of their images did not include the classification of chestnuts.

In the context of the restoration of CSFP in the Apennine Mountain Range in Italy and using advanced GIS-based tools and processes, the main aims of the present work were to develop a method able to a) identify the areas, from a geomorphological and pedological point of view, that can potentially allow for CSFP cultivation; b) provide maps that can be updated with further details and are easy to read by land planners, showing the areas suitable for CSFP; and c) propose a remote-sensing-based methodology able to identify the lands currently under cultivation for CSFP.

2. Materials and Methods

2.1. Study Area Framing

The study area chosen matches the Municipality of Castel del Rio (Barycentric coordinates 44°12′50″ N 11°30′15″ E), located in the Emilia-Romagna Region, in the hilly mountainous areas of the northern part of the Apennine Mountain Range in Italy (Figure 1).

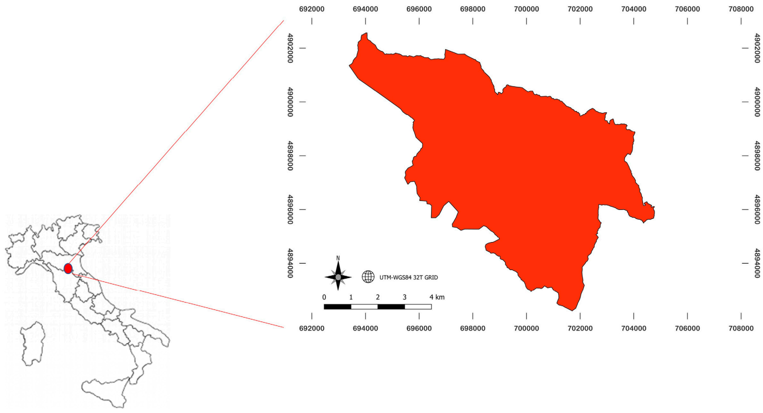

Figure 1. Study area: the Municipality of Castel del Rio, located in the Emilia-Romagna Region, Italy.

Fruit chestnut groves have been historically present in Castel del Rio as in almost all the mountainous areas of the Apennines. The Municipality of Castel del Rio did not undergo a serious abandonment of chestnut groves after World War II because of the creation of a protected geographical designation entitled "Marrone di Castel del Rio", which helps farmers to market their products better.

The study site is about 52.5 km^2 wide and has an average altitude of 476 m above sea level, ranging between 151 and 959 m above sea level (asl), and it is characterised by a warm temperate climate, with an average annual rainfall of about 1060 mm and an average temperature of about 13.7 °C; the hottest month is July with an average temperature of about 24.4 °C [38].

2.2. Indicators for the Assessment of Land Suitability for Chestnut Groves for Fruit Production

The land suitability of CSFP in the study area was investigated by considering altitude, exposure, slope gradient, lithology, and soil types. The data about altitude, exposure, and slope gradient were acquired from a digital terrain model (DTM), which is a topographic model of the bare Earth that can be manipulated with computer programs for further processing (i.e., altitude, exposure, and slope gradient). In the present study, the DTM was downloaded from the cartographic services of the Emilia-Romagna Region [39], with a 5 × 5 m resolution. The geolithological map, with a scale of 1:10,000, was freely downloaded from the geological surveys of the Emilia-Romagna Region [40]. Given the geological complexity of the study area, geolithological formations were grouped according to their characteristics, in particular alluvial deposits, sandstones, marls, and clay formations (Figure 2a). A land unit map (Figure 2b) was built by crossing different soil-forming factors (i.e., altitude, slope, geology, and land use). Each land unit included specific soil types according to these soil-forming factors (Table 1).

Table 1. Soil types, according to Soil Survey Staff [41], of the land units identified within Castel del Rio, Emilia-Romagna Region, Italy.

Land Units	Area (ha)	Soil Types
1. Recent sandy–gravelly alluvial deposits of river terraces. Land use characterised by arable land and orchards in flat areas and bushes, or with riparian woods in steep areas.	84	Typic Udiluvents with A–C horizons and moderately deep Fluventic Eutrudepts with A–Bw–C horizon sequence
2. Sandstone–pelitic formation affected by sheet erosion. Land use characterised by arable land or uncultivated bushland.	699	Thin or moderately deep Lithic Eutrudepts and Typic Eutrudepts with A–Bw–C horizons, Dystric Eutrudepts with A–B–C horizon sequence
3. Sandstone–pelitic formation with the prevalence of the sandstone component. Land use characterised by forest cover.	2618	Typic Hapludalfs with A–Bt–C horizons, Typic Dystrudepts and Dystric Eutrudepts with A–Bw–C horizon sequence
4. Sandstone formations and sometimes on-slope debris. Land use characterised by chestnut cover.	364	Typic Dystrudepts with A–Bw–C horizon sequence, Dystric Dystrudepts, and rarely Typic Eutrudepts
5. Clayey formations affected by erosion and cracks during the summer. Land use characterised by meadow–pasture or arable land.	245	Shallow to moderately deep Vertic Eutrudepts with A–Bw–C horizon sequence
6. Areas affected by existing or dormant instability with sheet and channelled erosion phenomena. Land use characterised by grass or bush cover.	725	Moderately deep Typic Eutrudepts with A–Bw–C horizons sometimes affected by waterlogging (Aquic Eutrudepts)
7. Areas affected by hydrogeological instability. Land use characterised by forest cover.	470	Typic Eutrudepts and Dystric Eutrudepts with A–Bw–C horizons, moderately deep, or more rarely shallow Lithic Udorthents with A–C horizon sequence
8. Areas characterised mostly by outcrops of clayey rocks, affected by strong erosion with the formation of gullies morphologies. Land use characterised by uncultivated lands or shrublands.	45	Shallow Lithic Udothents with A–C horizon sequence

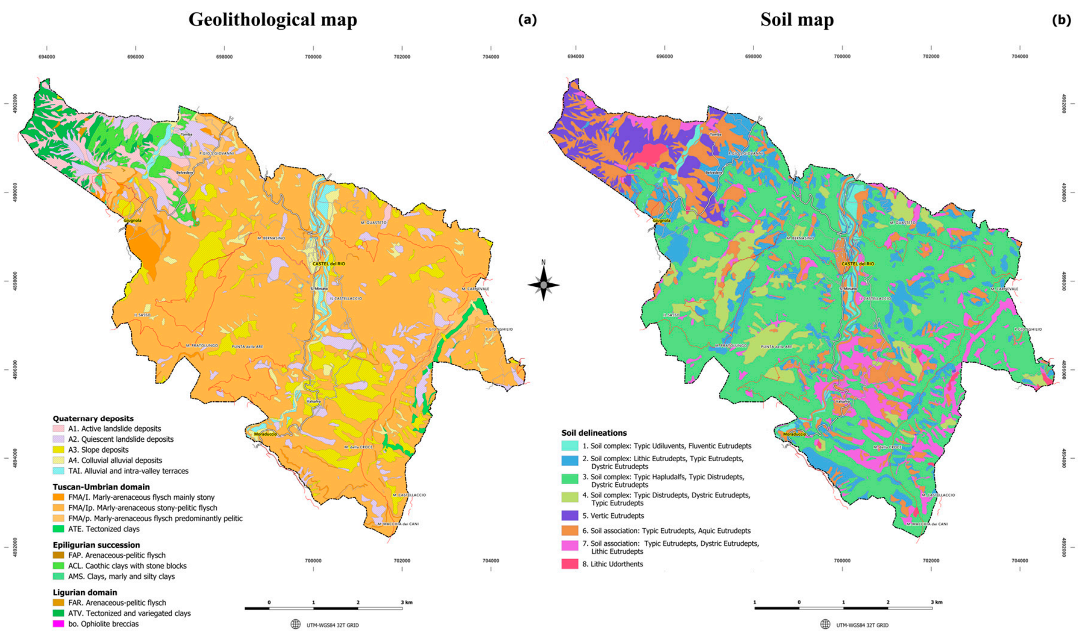

Figure 2. Geolithological (**a**) and soil (**b**) maps of Castel del Rio, Emilia-Romagna Region, Italy.

To build the suitability map for CSFP, the areas were considered suitable if located within the Castanetum phytoclimatic zone [42], namely at an altitude ranging between 300 and 1000 m above sea level [43–46] with north-facing exposition, from northwest to northeast [45,46] (Table 2). In this context, it is important to mention that the considered thresholds for altitude and exposure can be used for the northern part of the Apennine Mountain Range in Italy because of having the best climatic (air temperature and rainfalls) conditions for chestnut plants [46]. Regarding the slope gradient, it was considered suitable if it was less than 20°, allowing for the easy management of groves, including chestnut nut harvesting [47] and preventing intense soil erosion processes [48]. In terms of lithology, carbonate-free rocks as soil parent material (i.e., rhyolite, trachyte, pyroclastic deposits, siliceous rocks, sandstones, and greenschists) were considered. Such lithologies were selected on the basis of the most frequent lithological types found under chestnut grove cultivation in Italy [49] (Table A1 of Appendix A).

Table 2. Restriction rates for *Castanea sativa* Mill. cultivation for fruit production related to altitude, exposure, slope gradient, and lithology.

Geomorphological Characters		Restriction Rates			
		Absent	**Slight**	**Moderate**	**Severe**
Altitude [(a)]		300–1000 m asl	150–300 m asl	1000–1200 m asl or 50–150 m asl	>1200 m asl or <50 m asl
Exposure [(b)]		NE-NW	E-W	SW-SE	S
Slope gradient [(c)]		<20°	20–30°	30–35°	>35°
Lithology [(d)]	Igneous rocks	Rhyolite Trachyte	Diorite Volcanic tuffs	Gabbro Andesite	Granite Basalt
	Sedimentary rocks	Pyroclastic deposits Siliceous sandstones	Conglomerates Arenites Sandstones	Dolomitic limestones Calcarenites	Marls Marly clays Clays
	Metamorphic rocks	Greenschists	Schists	Marbles	Quartzite

asl = above sea level; [(a)] [43–46]; [(b)] [45,46]; [(c)] [47]; [(d)] Table A1.

From a pedological point of view, because of the preference for well-drained soils and soils with acidic conditions and a limited number of fine soil particles [50,51], the soil types considered suitable for CSFP were those included within the land units 2, 3, and 4, which developed on dystric facies carbonate-free (Figure 2b). In this sense, to check the reliability of the land units, within each suitable land unit, one soil profile was dug under CSFP and described according to Schoeneberger et al. [52]. The soil samples collected from the identified soil horizons were analysed in terms of pH, which was potentiometrically determined in a 1:2.5 solution ratio in deionised water. The particle size distribution was estimated using the pipette method [53]. The concentration of carbonate was estimated through the volumetric analysis of the CO_2 released by the contact of soil with a 6 M HCl solution [54]. Soil organic C (SOC) and soil nitrogen (SN) were determined using a CHN elemental analyser (Flash 2000, Thermo Fisher Scientific, Waltham, MA, USA). The cation exchange capacity (CEC) and the exchangeable cation contents were determined according to the method proposed by Orsini and Rémy [55] and modified by Ciesielski and Sterckeman [56]. Specifically, soil samples were suspended in 0.017 M hexamminecobalt (III) chloride solution. The amounts of the extracted Co and exchangeable cations were measured using an inductively coupled plasma optical emission spectrometer (Ametek, Spectro Arcos, Kleve, Germany). Afterwards, the soils were classified according to the keys of soil taxonomy of the Soil Survey Staff [41].

Once we defined the suitable topographic, altitudinal, lithological, and pedological conditions for CSFP, the suitability map was built by overlapping such suitable areas using the QGIS 3.26.3 software (Figure 3). The reliability of this procedure is supported by previous studies [22,37,57,58], which used several environmental data to evaluate the land suitability for certain crops in both agricultural and natural ecosystems. Within this process, a land-use map [59] was also included to exclude waterbodies and urban areas. The use of the open-source QGIS software was based on the fact that it allows users to analyse and edit spatial information, in addition to composing and exporting georeferenced maps [22]. QGIS supports both raster and vector layers; vector data are stored as point, line, or polygon features, and in addition, multiple formats of raster images are supported [22].

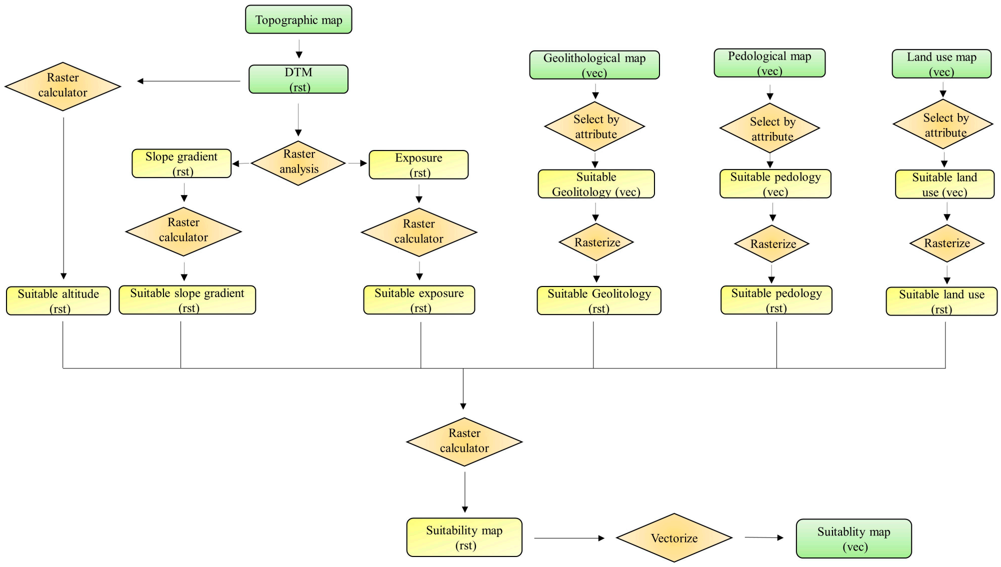

Figure 3. Flowchart of GIS-based processing for suitability map building. Between brackets, rst and vec indicate raster and vector file types, respectively.

2.3. GIS-Based Approach for the Identification of Areas Currently under Chestnut Grove Cultivation for Fruit Production

To identify the chestnut stands within the study site, Google Earth Pro remote-sensing images from April 2020 were collected. We used remote-sensing images in early spring because of the late vegetation restart growth of chestnut plants compared with the other forest plants that generally harbour within the areas where the chestnut plants grow. Conversely, images from the summer, autumn, and winter seasons cannot allow the identification of chestnut groves because of the similar vegetation stage among forest plants. Therefore, within the acquired remote-sensing images from Google Earth Pro, CSFP were easily identified because of both the late vegetation regrowth and the quincunx plantation pattern. The identified areas were delimited, and their extension was measured.

To evaluate the reliability of this approach, the obtained data from remote-sensing images were compared with the data from the 2017 land-use map of the Emilia-Romagna Region [59]. Further, the chestnut grove areas identified using remote-sensing images were compared with the suitability map. Both comparisons were performed using QGIS software.

3. Results

The analysis of the altitude showed that most of the study site (87.3%) can be considered suitable for the growth of CSFP, while unsuitable parts include the areas mainly located close to the Santerno river (Figure 4a). Regarding the exposure, the suitable area was 1968.8 ha, which amounted to 37.7% of the study site (Figure 4b). The mean slope was 22.6°, ranging from 0.05° to 58.4°, and the area showing the most suitable slope for CSFP represented 43.9% of the whole study area (Figure 4c).

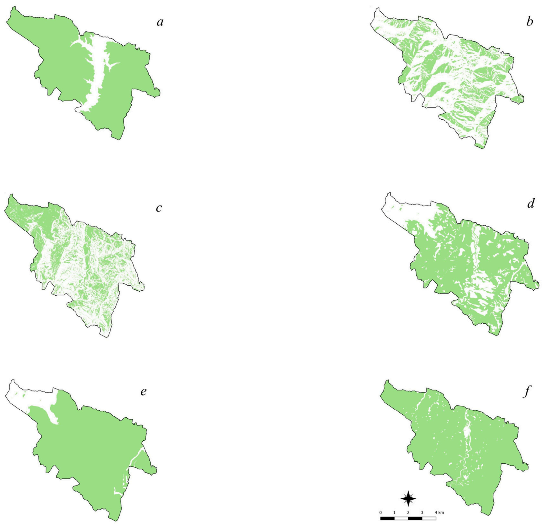

Figure 4. Suitable areas (green colour) in terms of altitude (**a**), exposure (**b**), slope gradient (**c**), soil type (**d**), geolithology (**e**), and land use (**f**) for the cultivation of chestnut stands for fruit production in Castel del Rio, Emilia-Romagna Region, Italy.

Through the analysis of the geolithology, it was revealed that the study site was mainly characterised by silicious sandstone formations (88.5%) and, to a lesser extent, clay formations (11.5%). The geolithological type defined as "silicious sandstone" formation, considered suitable for chestnut groves, was 4644 ha (Figure 4e).

The pedological map showed that the suitable area for CSFP accounted for 3681 ha, corresponding to 70.1% of the study site (Figure 4d). Generally, soils of such areas have pH values < 7 because of the absence of carbonates; however, subalkaline conditions can be also found due to the high base concentrations with positive effects on base saturation values.

The soil profiles dug within the land units confirmed the soil types reported within the pedological map (Table 3). Indeed, Alfic Dystrudepts, Typic Dystrudepts, and Dystric Eutrudepts were found. The described soils had a coarse texture with consequent low values of SOC content and CEC. The soils showed pH values of less than 7 with the exception of the soils in land unit 2, where some calcic horizons were observed, and the amount of exchangeable Ca was higher than the other land units. Most of the soils had a BS larger than 50%, and lower values were found in soils with lower pH values.

Through the overlapping of the land use with the areas suitable from topographical, geolithological, and pedological points of view, the suitable area for CSFP within the study site was 525.5 ha, accounting for 10% of the whole study site area (Figure 5). Most of the suitable area was observed in the northeastern part of the study site and at the northwestern exposition of the mountainous area located between the Sillaro and Santerno rivers.

The analysis of land use and georeferenced remote-sensing images showed that the CSFP currently cultivated within the study site spread for 379 and 414 ha, respectively, mainly located in the mountainous area between the Sillaro and Santerno rivers. Considering the CSFP area identified using remote-sensing images, it was mostly (98%) within the CSFP area defined by land use, while the additional areas were mainly observed in the western and eastern parts of the study site (Figure 6).

It is important to note that the CSFP area acquired through remote-sensing images highly matched that acquired through the land-use map, which suggests the high accuracy of such methodology (Figure 6). In addition, with the remote-sensing imaging methodology, it was found that the mean area of the CSFP was about 5.8 ha.

Table 3. Main morphological, physical, and chemical features of soil profiles dug within the land units 2, 3, and 4 of Castel del Rio, Emilia-Romagna Region, Italy.

Land Unit and Soil Type	Horizon	Depth (cm)	pH	$CaCO_3$	Sand	Silt	Clay	CEC	Ca_{ex}	Mg_{ex}	K_{ex}	Na_{ex}	BS	SOC	SN
				$g\ kg^{-1}$		$g\ kg^{-1}$				$cmol_{(+)}\ kg^{-1}$			%	%	%
Land unit 2 Typic Eutrudepts	A1	0–5	7.6	29.3	330	535	135	22.6	11.6	0.1	1.5	0.2	59.0	4.9	0.3
	A2	5–16	7.5	70.0	346	517	137	20.0	9.2	0.1	1.0	0.2	52.5	2.2	0.2
	Bw	16–28	7.5	100.1	256	483	261	15.0	7.8	0.1	0.8	0.1	58.5	1.3	0.1
	2Bw	28–41	7.6	0	168	530	302	27.3	12.4	0.1	1.3	0.1	51.0	0.7	0.1
	2BC	41–60+	7.5	0	89	527	384	32.6	14.3	0.1	1.8	0.1	49.7	0.5	0.1
Land unit 3 Alfic Dystrudepts	Oe	0–0.5	4.9		—	—	—	21.1	7.1	3.4	0.7	0.2	53.6	22.7	1.1
	A1	0.5–4	4.8	0	387	403	210	7.3	0.8	0.7	0.2	0.1	24.5	4.5	0.2
	A2	4–7/9	4.5	0	363	427	210	9.5	1.0	0.7	0.2	0.1	20.4	5.6	0.2
	AB	7/9–14	5.0	0	366	403	231	8.4	0.9	0.2	0.0	0.0	22.4	1.6	0.1
	Bt	14–20	4.9	0	336	398	266	7.4	0.3	0.3	0.0	0.1	8.3	1.1	0.1
	BC1	20–35	5.4	0	355	461	184	8.5	0.4	0.6	0.0	0.1	12.0	0.8	0.1
	BC2	35–46	4.9	0	362	432	206	8.9	0.4	0.8	0.0	0.1	14.7	1.1	0.1
	C	46–60+	5.6	0	450	392	158	6.5	0.5	0.9	0.0	0.1	22.9	0.2	0.0
Land unit 4 Dystric Eutrudepts	A1	0–3	6.9	0	350	454	196	20.3	8.3	1.4	0.3	0.1	49.8	5.3	0.3
	A2	3–10	7.2	0	328	490	182	14.7	6.4	1.0	0.1	0.1	52.1	2.4	0.2
	AB	10–23	6.9	0	327	487	186	9.3	5.1	0.9	0.1	0.1	67.0	1.2	0.1
	Bw1	23–38	6.9	0	266	495	239	9.7	4.6	1.0	0.0	0.1	58.4	0.6	0.0
	Bw2	38–50	6.9	0	264	441	295	9.3	4.1	1.0	0.0	0.1	57.0	0.6	0.0
	BC	50–60+	6.8	0	306	439	255	8.9	3.5	1.1	0.0	0.1	52.4	0.4	0.0

CEC = cation exchange capacity; Ca_{ex}, Mg_{ex}, K_{ex}, and Na_{ex} = exchangeable Ca, Mg, K, and Na, respectively; BS = base saturation; SOC = soil organic carbon; SN = soil total nitrogen.

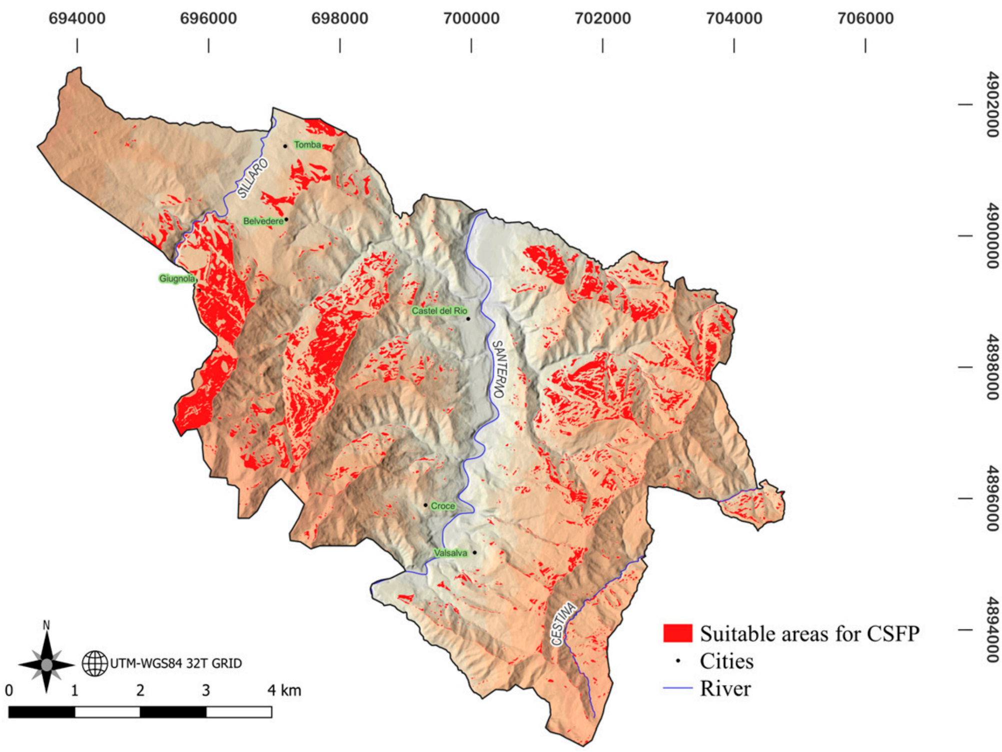

Figure 5. Suitability map for chestnut stands for fruit production (CSFP) for Castel del Rio, Emilia-Romagna Region, Italy.

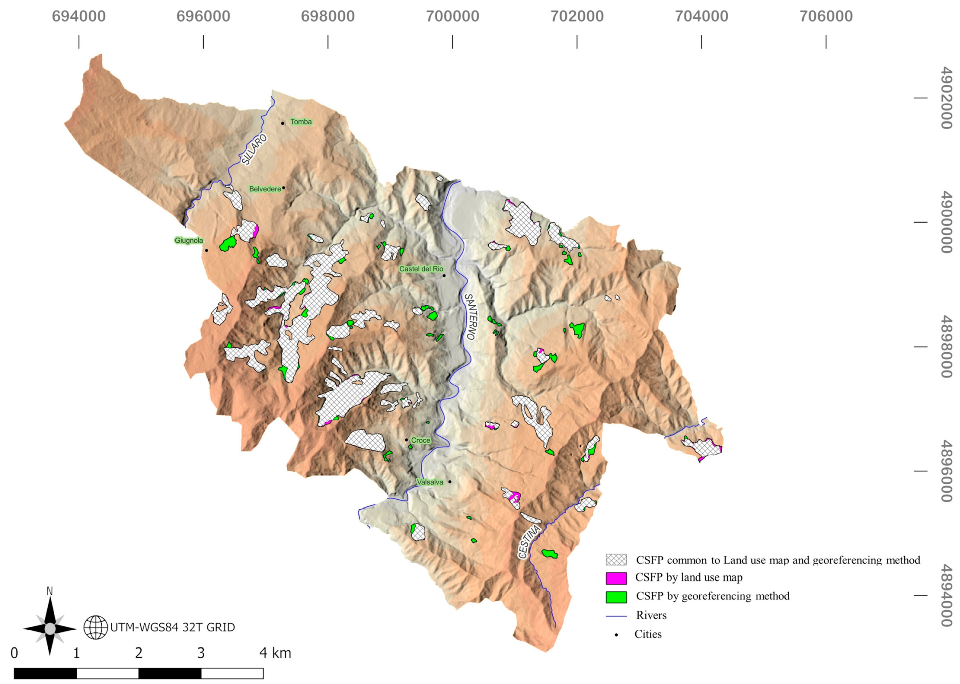

Figure 6. Map of Castel del Rio, Emilia-Romagna Region (Italy), showing the areas for chestnut stands for fruit production (CSFP) identified only with the land-use map (purple area), only with the georeferencing approach (green area), and with both methodologies (squared area).

The overlapping between the currently CSFP cultivated areas identified with remote sensing and the CSFP suitable map revealed that 59% of currently cultivated chestnut groves are not within the suitability area (Figure 7). In addition, most of such CSFP located outside of suitable areas had a non-suitable slope gradient (>20°).

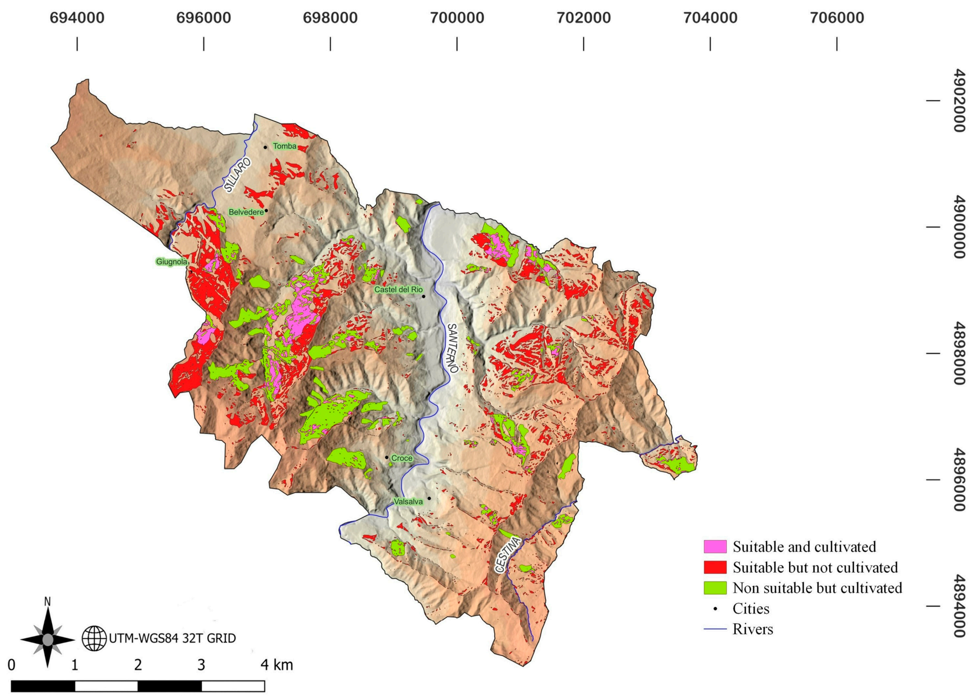

Figure 7. Map of Castel del Rio, Emilia-Romagna Region (Italy), showing the suitable areas for the cultivation of chestnut stands for fruit production (CSFP) and currently used for CSFP, the suitable areas for the cultivation of the CSFP but currently not used for CSFP, and the overlapping of suitable and cultivated CSFP areas.

4. Discussion

The GIS-based approach was successfully used in the current study to evaluate land suitability for chestnut cultivation. Six parameters, namely land use and topographic features (altitude, slope gradient, and exposure), as well as lithological and pedological features, were taken into consideration.

The altitudinal suitability map showed that most of the study site can be potentially suitable for CSFP. The unsuitable areas in terms of altitude were located close to the Santerno river. In these areas, the altitude was lower than 300 m asl where the mean air temperatures were greater than 15 °C and annual rainfall below 600–700 mm, and therefore they were commonly excessively warm and dry for the optimal growth and development of chestnut groves [60,61]. In fact, Pérez-Girón et al. [60] and Freitas et al. [61] stated that high temperatures do not allow budburst, flowering, fruit set, and maturation other than to maintenance costs. Further, the authors reported that low precipitation reduces plant development, leading to the production of smaller organs hampering flower production and grain filling, and limiting the size and number of individual leaves. The unsuitable climatic condition of this area was confirmed by the absence of chestnut stands [59].

Unlike the altitudinal map, the exposure map defined most of the study site as unsuitable for CSFP because of the southern exposition. Exposure plays a key role in terms of chestnut plant growth and nut production [45,46]. Specifically, the plants with southern exposure receive more direct heat than the ones with northern exposure, resulting from the sun drying both the soil and the vegetation, which may cause water stress [45,46,55–57]. This is particularly important during the flowering stage, which occurs in the summer months at Italian latitudes, resulting in thermal stress and finally less or no fruit development [41,42,62–64].

Although the study site was characterised by a hilly mountain landscape, the areas with a slope of less than 20° accounted for 43.9% of the entire Castel del Rio area. A low degree of slope prevents the occurrence of intense soil erosion processes [65], which promote soil deepening [66,67], with possible positive consequences on root development and plant production [68,69]. In addition, the limited soil erosion occurring within the areas with a slope gradient < 20° could promote soil organic matter accumulation [70] known to improve soil ecosystem services including plant growth and yield [69,70]. Besides the negative effects of high slope gradients on soil quality, although there is no basic and common guideline for a favourable slope for chestnut production, steep slopes cause difficulties during harvest with a consequent increase in harvesting costs. However, it is important to point out that although slope gradients > 20° cannot be considered suitable for CSFP, such areas could be addressed for the establishment of chestnut groves for wood production due to the recent development of machines and technologies that can also be used in steep areas [71,72]. Slope gradients > 20° prevent agricultural mechanisation with a consequent increase in management costs. Conversely, low slope gradients allow for the cost-effective management of farms, thus facilitating agricultural practices [73]. In addition, low slope gradients limit soil erosion processes, which, in turn, positively affect crop yield [74].

In terms of the lithological and pedological features, most of the study site can be considered suitable for CSFP. These results are in accordance with those reported by Sanesi [75] and Antoniazzi [76], which, through a study conducted within the Santerno river valley, showed the presence of chestnut stands on sandstone formations. In this context, it is important to highlight that the suitable soils had generally "dystric" features, namely an effective base saturation of less than 60% [41], which matched with the silicious sandstone formation from which they developed. In addition, such matching would indicate the greater role of parent material on soil properties than the other soil-forming factors in the present study site.

Although CSFP was historically present within the considered study site, the overlapping of the areas suitable in terms of altitude, exposure, slope gradient, lithology, and soil types showed that the suitable area for CSFP accounted only for 10% of the study site. This area included just 24.6% of the CSFP that are currently cultivated, suggesting the need for incentives from institutions to farmers to use such suitable areas for the creation of CSFP. Although most of the suitable area was observed in the northeastern part of the study site and the mountainous area located between the Sillaro and Santerno rivers, several suitable areas spread all over the study site. However, they showed a limited area ($\leq$50 m^2), which does not allow economically sustainable chestnut production. Further, the limited suitable area would indicate the distribution of chestnut groves also in non-suitable areas. Indeed, through a comparison of the areas currently used for CSFP and the suitability map, most of them were in non-suitable areas, where the most limiting factor was the slope gradient. To reduce the soil erosion processes occurring in areas with high slope gradients, mulching and the conservation of grass cover are suggested [77]. However, to reduce soil erosion and facilitate cultivation operations, terracing is the most recommended intervention [77–79]. In this regard, despite non-suitable areas having slope gradients of >20°, they still had CSFP because of terracing, which was the major morphological transformation implemented by farmers in these mountainous areas to obtain cultivable land in steep areas [80–82]. Terraces increase soil organic carbon accumulation, slow down the erosive power of the surface water flow, and improve soil water storage [82–84]. However, terracing needs high investment and maintenance [85,86], and the presence of farmers who would maintain the terraces in these mountainous areas. Therefore, land abandonment in terms of rural depopulation and/or the lack of management of CSFP could cause soil degradation in such areas [82,87]. Besides this, the obtained suitability map highlighted the potential loss of 59% of the currently cultivated CSFP in the next years. Such loss will be observed if the price of chestnuts does not also cover the costs related to CSFP management practices coping with degradation processes due to unsuitable conditions. Although most of the currently cultivated CSFP can be potentially lost, the suitability map showed that a wide area of the study site can be converted to CSFP (423 ha) in light of the demand increase for chestnuts due to their health benefits [88,89]. In this sense, we do not know if such areas were CSFP in the past and, therefore, need to be restored; regardless, the establishment of CSFP might promote the improvement of soil quality [87].

Although the suitability map can be a helpful tool for land use planning, the knowledge of the current use of territory results is necessary to foresee the management practices that should be carried out for land conservation and or conversion [90]. In this context, the present study shows the reliability of remote-sensing images to identify the currently cultivated CSFP. However, the main drawback of such a procedure is that it is highly time-consuming because the CSFP areas should be manually identified. To cope with this issue, since CSFP are characterised by a distance of 10 m between chestnut plants and a later vegetation regrowth than other plant species, CSFP areas can be identified using a semi-automatic classification plugin in QGIS [91,92], which is cost-effective. As a whole, the remote-sensing images approach showed a high fragmentation of CHEF, which is a generally negative feature for agriculture [93]. Within the investigated area, our findings suggest the promotion of land conversion to CSFP in suitable areas. Conversely, the CSFP located within unsuitable areas might be abandoned, especially those of small dimensions, to reduce the fragmentation.

5. Conclusions

The present work aimed to identify the areas that can potentially allow for CSFP cultivation by taking into consideration the geomorphological and pedological features, to provide maps that are easy to read by land planners and show the areas suitable for CSFP, and to propose a remote-sensing-based methodology able to identify the lands currently used for CSFP. Although the considered study site was recognised as an important area for chestnut production, the built suitability map demonstrated that only 10% of this area can be considered suitable for chestnut cultivation. Further, the remote-sensing images showed that most of the currently cultivated CSFPs were not within such suitable areas (59%) and, therefore, can undergo degradation processes mainly due to the high slope gradients. In this regard, it is important to highlight that, in some of these stands, farmers transform the land morphology by building terraces to obtain cultivable land on steep slopes. The limited suitable area for CSFP detected in the present study indicates that policymakers should consider careful planning in mountainous areas to promote chestnut cultivation within the identified suitable areas. Further, since most CSFP are currently cultivated within non-suitable areas, policymakers should help farmers in the implementation of ameliorative interventions to undertake both chestnut production and land conservation. The high matching observed between the CSFP areas acquired through remote-sensing images with those acquired through the institutional land-use map suggests the high accuracy of remote sensing to identify CSFP. This fact implicates the helpfulness of remote sensing for land planners in acquiring detailed information about land use.

Due to its easy execution, the methodology used for building land suitability maps coupled with land-use monitoring using remote-sensing images can be applied to CSFP at a wider geographical scale and to other forest and agricultural plants. Regardless of such potential, the present study highlights the need to have detailed lithological and pedological data to obtain reliable land suitability maps.

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Appendix A

Table A1. Geolithological formation types and morphological features of Italian areas currently under chestnut stand cultivation for fruit production cultivation.

Region	Geolithology	Municipality/Locality	Altitude m asl	Slope %	Sources
Piedmont	Mycascists, gneisses, gneiss glanders	Low Alpine slopes (Turin and Cuneo)	400–900	30–60	[94]
	Detrital conoids referred to as gneisses	Low Alpine slopes (Turin and Cuneo)	300–900	30–80	[94]
	Siliceous matrix colluvium with gneiss predominance	Low mountain slopes (Verbano)	200–700	30–60	[94]
	Porphyries with mica-schists and quartzites included	Gentle mountain slopes (Vercellese, Novarese)	400–700	15–40	[94]
	Porphyries covered by ancient alluvial deposits	Transition between plain and pre-alpine reliefs	200–400	10–20	[94]
	Gneiss	Biella and Turin Pre-Alps	400–700	15–40	[94]
Lombardy	Schistous and micaceous gneisses	Bacino torrente Bitto di Gerola (SO)	820–850	50–60	[95]
	Slope debris gneisses and mica-schists	Val Grosina (SO)	670–700	35–40	[96]
	Marly limestones, dolomitic limestones, and dolomites	Bergamasque Hinterland	270–670	35–40	[97]
	Ferretised pebbles and sands in an advanced state of alteration	Pinewood of Appiano Gentile-Tradate	320–375	5–40	[98]
Trentino	Hard limestones, porphyries, siliceous sandstones, and glacial siliceous deposits	Valle delle Chiese (Darzo, Lodrone, Daone)	400–700	35–50	[99]
	Rhyolites, rhyodacites, phyllites, and mica-schists with widespread glacial overburden	Valsugana (RoncegnoT., Strigno, Castagnè, Caldonazzo)	500–900	25–45	[99]
	Limestones and marly limestones with possible glacial cover with mixed lithology	Brentonico Plateau (Castione)	200–800	30–40	[99]
	Hard limestones, marly limestones with glacial cover with mixed lithology	Upper Garda Trentino (Nago, Drena, Tenna)	200–600	35–45	[99]
	Rhyolites, rhyodacites, and dacites with glacial overburdens	Cembra Valley (Albiano)	500–800	30–60	[99]
Friuli V.G.	Flysch with alternating arenites with calcareous-siliceous marls	Pre-Alpine reliefs Col Budoia	100–150	20–30	[100]
	Conglomerate of predominantly calcareous nature with arenaceous and itic interlayers	Pre-Alpine reliefs Sequals Col Pallotta	300–350	25–35	[100]

Table A1. *Cont.*

Region	Geolithology	Municipality/Locality	Altitude m asl	Slope %	Sources
Veneto	White mica phyllites, corite, and albite	Venetian Pre-Alps	450–650	10–30	[101]
	Calcareous conglomerates in karst morphologies	Montello and Berici Hills	100–200	5–10	[102]
	Acid volcanic rocks (rhyolites and trachytes)	Euganean Hills	300–600	15–30	[102]
Emilia-Romagna	Sandstones and pelitic sandstones	Upper Frignano (MO) Upper Reno Valley	900–1000	50–70	[103]
	Pelitic limestone flysch	High Apennines Reggiano-Parmense	800–1000	40–60	[104]
	Pelitic sandstones and marly limestones	Upper Santerno and Savena Valleys	850–1000	30–50	[105]
	Conglomeratic-pelitic sandstone deposits	Sillaro and Lavino Valleys	450–600	10–38	[106]
	Sandstones with arenaceous-pelitic intercalations	Upper Idice Valley	250–500	30–45	[107]
Tuscany	Quartz-latitic volcanites and pyroclastic deposits	Monte Amiata (Arcidosso, Castel del Piano, Seggiano (GR))	950–1250	10–35	[108]
	Silty schists, marls, and sandstones	Londa (FI), Vernio (PO)	500–700	35–60	[108]
	Turbiditic flysch, marls, and marly clays	Camporgiano (LU)	50-160	35-40	[108]
	Quartzose-felspathic sandstones	Arezzo, Poppi (AR), Firenzuola (FI), Molazzano (LU)	400-900	14-40	[75]
	Pebbly sediments and polygenic conglomerates interbedded with clayey sands	Aulla, Nardi (MS)	150–270	10–25	[108]
	Calcareous polygenic conglomerates	Aulla (MS)	100–400	15–30	[108]
Latium	Earthy tuffs with black and white pumice	Sabatini Mountains	300–700	10–20	[109]
	Earthy tuffs	Montesanti	980–1000	25–30	[110]
Abruzzo	Pelitic-arenaceous alternation with debris-colluvial belts at the base of slopes	Rocca S. Maria, Montorio del Vomano (TE) Montereale (AQ)	800–1200	20–35	[111]
	Ancient terraces with fluvio lacustrine and clastic volcanic sediments	Oricola, Carsoli (AQ)	500–800	0–13	[111]
	Linear slopes on marly limestone substrates	Monreale, Monte Genzano, Pettorato sul Gizio (AQ)	800–1200	20–35	[111]
Molise	Dolomitic limestone affected by pyroclastic cover	S. Massimo	850–900	10–20	[112]

Table A1. *Cont.*

Region	Geolithology	Municipality/Locality	Altitude m asl	Slope %	Sources
Campania	Mesozoic carbonate rocks with pyroclastic overburden	Lattari and Picentini Mountains (Campania Region, 2004)	300–1100	35–60	[113]
	Carbonate rocks with pyroclastic overburden	Upper Telesina Valley	600–750	20–30	[113]
	Mesozoic dolomite and limestone with pyroclastite cover	Caruso and Cuculo Mountains mountain system	100–600	15–35	[113]
	Sandstones, marly sandstones, and conglomerates	Pre-Apennine hills of basso Ufita and Conca Avellinese	300–400	15–30	[113]
	Conglomerates and sands	Pre-Apennine hills of Benevento	300–400	25–40	[113]
	Clay formations with pyroclastic coverings	Irpinia and Sannio hills	250–450	20–30	[113]
	Fluvio-lacustrine deposits	Upper Sele Valley	300–500	15–25	[113]
	Fluvio-lacustrine deposits	Lauro-Baianese Valley	150–300	10–20	[113]
Basilicata	Vulture volcanic reliefs with pyroclastic coverings	Santa Maria	700–800	10–15	[114]
Calabria	Phylladic schists and granites	Coastal chain and Presila of Cosenza	300–900	10–30	[44]
	Alteration sand of granites	Sila Greca, Upper Ionian Cosenza	500–1000	20–30	[44]
	Alteration granites	Presila of Crotone and Catanzaro	800–100	15–25	[44]
	Phyllites, leucoscists, biotic schists	Serre of Catanzaro and M.te Reventino	600–900	10–25	[44]
	Alteration sand of granites	Serre Vibonesi	600–900	10–20	[44]
	Heavily altered granite rocks and tertiary conglomerates	Western and Eastern Aspromonte	300–1200	15–40	[44]
Sardinia	Palaeozoic granites and schists	Mandrolisai. Municipalities of Desulo, Tonara, Balvi, Aritzo	600–700	20–30	[115]
	Metavolcanites and ignimbrites	Goceano, Monte Pisani	700–900	20–25	[115]
Sicily	Heavily weathered sandstones	Erei Mountains, Rossomanno (EN)	550–890	15–25	[116]
	Inert quartz-arenites to micaceous pelite	Forest of Ficuzza. Rocca Busambra (PA)	600–1000	10–15	[117]
	Altered calcarenites and limestones	Mount Peloritani, Musolino, Novara (ME)	380–1050	10–15	[116]
	Basic volcanic rocks	Mount Etna, Randazzo, Pirao (CT)	600–1210	10–20	[116]

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