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Lessons learned from the past: forestry initiatives for effective carbon stocking in Southern Italy

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Abstract

Calabria (Italy) is a particularly interesting region of the Mediterranean basin from the perspective of forest management due to the extension of reforestation activities aimed at soil conservation. According to international agreements, these reforestation activities fulfill other functions as well, including carbon storage. Thus, Calabria was selected as a representative area for a study on the different typologies of forest plantations to verify the effects of these functions. Results showed a significant increment in carbon stock compared to the previous land use (i.e. arable land and pastures) and how the average carbon stock per hectare varies in relation to the species considered at the above- and below-ground levels. Carbon stock was higher in conifers (Calabrian pine, Douglas fir) and lower in broad-leaved trees (Turkey oak, European chestnut). The study analyses demonstrate how, based on different intensities of thinning, the carbon eliminated by trees is reconstituted over time in quantities larger than those eliminated by cutting. This latter aspect is relevant, as forest management allows the partial removal of biomass produced without negatively affecting carbon stock. Consequently, reforestation and sustainable forms of forest management are powerful strategies for mitigating the effects of climate change.

Keywords: Forest biomass, reforestation, carbon stock, silvicultural interventions, stand density.

1. Introduction

Since the 90s, the expansion of forest areas, their conservation and the replacement of fossil fuels with bio-energy resources constitute one of three objectives to be pursued for the mitigation of environmental change issues, as requested by the Kyoto Protocol (UNFCCC 2005). It is a well-known fact that the Convention on Climate Change demands the conservation of carbon stock on all continents, the promotion of carbon sinks and their improved performance (Pettenella and Zanchi 2006, IPCC 2019). Indeed, about one fifth of the CO_2 emissions generated worldwide is related to deforestation and the excessive exploitation of forests (Van Der Werf et al. 2009, Harris et al. 2012, Kim et al. 2015). The Kyoto Protocol presented flexible strategies for achieving reduced emissions targets (Fischlin et al 2006). An example is the use of the so-called sinks obtained through the cultivation of agricultural land, grassland and the management of forest areas (Poeplau et al. 2011, Gattinger et al. 2012). For the latter, reference is made to both the management of existing forests and the extension of forest areas (Piao et al. 2018). These activities are mainly carried out by the establishment of new plantations on land not covered by forest vegetation and by the enhancement of carbon stocks of existing forests (Liu et al. 2018, Ghazoul et al. 2019). On the other hand, forests can sequester atmospheric carbon to mitigate climate change, a topic which has been of considerable interest in plant ecology for decades (Reichstein et al. 2007).

Between 1990 and 2015, the forest area in the territory of the European Union (EU-27) increased overall by about 12.9 million hectares (FAO 2018). Of these, approximately 1.5 million are the result of programs promoted by European policies, while the remaining part is due to the abandonment of pastoral practices and the consequent spontaneous return to wooded forest vegetation (Ministerial Conference on the Protection of Forests in Europe 2015). Hence, the forestry sector has actively taken on the task of contrasting climate change according to the obligations of the Kyoto Protocol (Ciccarese et al. 2005). However, carbon sinks are only complementary to activities aimed at reducing emissions at the source. Carbon sinks allow saving time in order to effectively reduce emissions through technological development by targeting energy savings and replacing fossil fuels (Pettenella and Guerci 2010).

According to the estimates of the National Inventory of Forests and Forest Carbon Sinks (INFC 2009), the organic carbon in the above-ground component of forests (living trees, renewal and shrubs) amounts to 472.7 Mt, while the amount removed from the atmosphere annually is about 12.6 Mt. Dead wood contains 24.9 Mt of organic carbon and litter contains 28.3 Mt, while the amount of organic carbon in the organic and mineral horizons of the soil is estimated to be equal to 715.7 Mt. Forests in Italy retain a total of 1.24 billion Mt of organic carbon (INFC 2009). The increase in forest areas leads to a rapid uptake of carbon in the biomass (at approximately 1-10 Mg C ha^{-1} $year^{-1}$, according to the species) and soil, representing the most stable carbon fraction over time, with residence intervals of 300 to 400 years (Scarascia Mugnozza and Matteucci 2010).

The carbon stock process following reforestation has been examined by some authors in different contexts (Deng et al. 2016, Lukić et al. 2015). The highest carbon increase was found in farmland than in natural forests (+53%), while a more limited, positive carbon increase (+18%) was detected in forest plantations. Below-ground carbon uptake is highly variable, yet approximate values indicate an increasing rate of 0.1 to 0.3 Mg of C ha^{-1} $year^{-1}$ (Paul et al. 2002, Del Galdo et al. 2003, Cannadell et al. 2007). The contribution of Mediterranean maquis to carbon stock is also significant (Ruiz-Peinado et al. 2013, Sanesi et al. 2013, Marziliano et al. 2015a).

Several legislative agreements at national and international level have promoted the increment of forest areas through reforestation interventions, even prior to the implementation of the Kyoto Protocol (Nabuurs et al. 2017). In the long term, the effects resulting from forest plantation initiatives (mainly for soil erosion protection) must be considered along with others related to biodiversity and carbon sequestration, as well as the availability of forest products. Reforestation also has important implications on the hydrology of basins (Hartanto et al. 2003). The presence of vegetation in fluvial systems is encouraged for their environmental function, as it impacts flood risk and the solid transport (D'Ippolito et al. 2019). These results highlight the fact that reforestation must be considered from a global perspective (Bastin et al. 2019).

Since the beginning of the last century, reforestation has characterized the forestry activity of several Mediterranean countries, attested by considerable relevance in the vast number of works carried out and their positive effects on soil conservation and socio-economic involvement (San Roman Sanz et al. 2013). The interventions were aimed at replenishing forest areas that had previously been destroyed in order to supply more land for agriculture and the primary needs of mountain populations. In Portugal, 23,500 hectares were added to an existing 420,000 from 1896 to 1936 (Del Galdo et al. 2003). In Spain, around 4.5 million hectares were reforested between 1940 and 1984 (Costa-Tenorio et al. 2005). In Italy, over 1 million hectares were reforested from the last century to 2008 (Corona et al. 2009).

Mediterranean ecosystems have undergone long and continuous environmental degradation because of ancestral land use practices, dependence on local socio-economic resources, natural fire regimes or the intentional use of fires (Granados et al. 2016). All together, these actions have had a strong impact not only on ecosystem dynamics but also on landscape structure and functionality (Tomaz et al. 2013). Calabria is one of the most interesting Mediterranean regions for the extension of reforestation works carried out in recent decades (Marziliano et al. 2015b, Coletta et al. 2016, Scarciglia et al. 2020). Reforestations cover a total area of just over 112,000 hectares, which is equal to 30% of the amount reforested throughout Italy in the period from 1957 to 1967 (Iovino et al. 2015). This finding is relevant because, firstly, it allows this region to become a benchmark for many others in the Mediterranean environment and, secondly ,the works were carried out at an unprecedented spatial and temporal scale for Italy, with the main purpose of remedying the hydrogeological instability that the regional territory underwent in the mid-50s (D'Ippolito et al. 2013).

Research objectives

The main objective of this note is to present an assessment of carbon stock in selected reforested areas of Calabria (Southern Italy). The specific objectives can be summarized by raising the following questions:

(i) Have carbon stocks increased or decreased due to land use changes resulting from reforestation? And to what extent?

(ii) How much biomass was produced and how much carbon was stored, both above- and below-ground, in the reforestation of conifers (Calabrian pine and Douglas fir) and broad-leaved trees (European chestnut and Turkey oak)?

(iii) What have been the variations of biomass and carbon over time in relation to stand density?

(iv) What were the effects of thinning on carbon stock?

Materials and methods

Study area

The study site lies in the water catchment area of the Arente river, a right tributary of the river Crati in the central-northern region of Calabria, more specifically, in the province of Cosenza (Southern Italy) (Fig. 1). The total area of the Arente river basin covers about 7,265 hectares.

This area is considered important for several aspects:

(i) reforestation and forest management have been combined and achieved high levels of carbon stock, desertification contrast and biodiversity enhancement;

(ii) reforestation has been carried out with the primary objective of soil conservation, in compliance with the guidelines of national and international agreements issued in subsequent years (i.e. concerning desertification, carbon stock, biomass production), allowing an evaluation of the overall results achieved;

(iii) artificial forest cover has led to a reduction in water erosion, an increase in soil and organic matter content (C-sink), and the creation or conservation of habitats favoring the development of spontaneous fauna and flora; moreover, it has favored restoration of the territory by reconstructing the forest landscape;

(iv) in addition to soil protection, reforestation has also contributed to containing the chemical and biological degradation of soil (Scarciglia et al. 2020). The application of an analytical framework (Roggero et al. 2011) has shown that the study area is an ideal site for combatting desertification in the Mediterranean region.

This area is representative of numerous cases in the territory of Calabria and can act as a model for many other Southern European sites where an integrated approach to soil conservation was adopted in the second half of the 90s. In Calabria, afforestation has constituted a significant sector of activities. This afforested area represents about 30% of the entire Calabrian territory and 40% of the forest area.

(insert Fig. 1 here)

Climate, land and soil characteristics

In Calabria, reforested areas form systems that cover several hundreds of hectares and are mainly distributed in elevated hilly zones at altitudes ranging from 900 to 1,500 m a.s.l., between a latitude of approximately 39°22' and 39°25' North and a longitude of 3°53' and 3°55' East (Nicolaci et al. 2014). Forest vegetation is attributable to the horizons of the basal plain and mountain belt. The first horizon rises to an altitude of 1,100 m a.s.l. and has been characterized in the past by a massive presence of oaks, essentially Turkey oak

(*Quercus cerris* L.), Italian oak (*Q. frainetto* Ten.), Macedonian oak (*Q. trojana* Webb.) and a smaller number of European chestnut trees (*Castanea sativa* Mill.). The second horizon starts higher than 1,100 m a.s.l. and continues up to the highest mountains (e.g. Monte Scuro) at 1,633 m a.s.l.; it is characterized by natural formations of Mediterranean Black Calabrian pine (*Pinus nigra* Arn. Var. Calabrica) and beech (*Fagus silvatica* L.) (Barbati et al. 2014).

In accordance with the phytoclimatic classification of Pavari (1916), reforestation interventions between 900 and 1,200 m a.s.l. have been found in the *Castanetum* area and above this altitude to the highest mountains in the *Fagetum* area. Based on the classification of Rivas Martinez (1995), reforestation at lower altitudes corresponds to the Mediterranean oceanic bioclimate, upper meso-Mediterranean, and superior sub-humid types, while reforestation at higher altitudes corresponds to the temperate oceanic, lower subalpine, and upper humid climate types. The former bioclimatic typology is common in the western zone of the Mediterranean and especially the Iberian Peninsula, including the oceanic coasts of Portugal, Corsica, and the French Mediterranean. In the eastern zone it is common along the coasts of Albania, Greece and the Aegean Sea. The latter temperate sub-Mediterranean oceanic climate type is found along the northern oceanic coasts of the Iberian Peninsula and the southern French coast. Moreover, it is present along the French coasts immediately upstream of the Mediterranean oceanic type. In the eastern zone the sub-Mediterranean oceanic type is specific to the Adriatic coasts of Slovenia, Croatia, Montenegro and the inland regions of Albania and Greece.

The average annual rainfall, recorded by the weather stations of San Pietro in Guarano (660 m a.s.l.), Camigliatello Silano (1,291 m a.s.l.) and Monte Curcio (1,730 m a.s.l.), is 992, 1,634 and 1,261 mm, respectively. The average annual temperature recorded for the same stations is 14, 9.2 and 6.8°C, respectively, with the coldest average being 5.2, 0.3 and 3°C; during the warmer months the temperature rises to 22.7, 18.4 and 15.4°C, respectively.

Based on the United States Department of Agriculture (USDA) soil classification (Soil Survey Staff 2010), most of the reforested areas fall under the order of inceptisols (undeveloped soils), particularly in the group of Typic Dystrudepts, Humic Dystrudepts and Humic Psammentic Dystrudepts. The first two groups are typical of moderate slopes where the soils are moderately deep and acid to sub-acid, have a common skeleton and high surface stoniness, medium texture, moderate water reserve and good drainage. The third group is largely found in the central area of the basin and on steep slopes, and is composed of markedly altered granitic rock. These soils are shallow and acidic, have a poor skeleton and coarse texture, a low water reserve and rapid drainage.

Reforestation of Calabrian pine and Douglas fir

Reforestation in the study area was carried out starting in 1955, although it mostly began in 1958 and lasted until the early 70s. Initially, almost only Calabrian pine (*P. nigra* Arn. Var. Calabrica) was planted, and in some areas mixed with Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco); subsequently, Calabrian pine was planted in smaller areas with Douglas fir, chestnut, and oak. Other conifers formed mixed and very heterogeneous stands within which they became sporadically present. Due to the irregular spatial distribution of the different exotic species used, these stands were considered in the note only for calculating total forest area.

- Calabrian pine

Calabrian pine forms pure systems of different sizes that are distributed throughout the mountainous sector of the basin. Planted areas are separated by naturally wooded areas of Calabrian pine and beech woods, many of which are coppices in conversion to high forests.

The variability of soil conditions has had an impact on reforestation techniques. The number of trees per hectare ranged from 2,000 to 3,250 in relation to soil preparation techniques (steps, steps and holes), which differed according to soil conditions. Only locally sowed plantations were carried out in the autumn/winter before snowfall, which occurs starting from the month of December. The forest planting stock consisted of 2- or 3-year-old seedlings. The same techniques were also applied where Calabrian pine was mixed with Douglas fir, starting with 2,000/2,500 trees per hectare; the distribution of Douglas fir trees was on average one Douglas fir for every 7/8 pines. These reforestation works were carried out from 1955 to 1974; more than 90% of the area was established in seven years and 47% in just two years.

- Douglas fir

In addition to its mixed consortia with Calabrian pine, Douglas fir also constitutes pure stands. This species was initially planted in the early 1960s and on larger areas about a decade later. It was planted from 800 m to 1,200 m a.s.l. in areas sheltered from the wind and in better soil conditions than those in which the Calabrian pine was planted. In shallow soil Douglas fir spreads its roots superficially increasing the risk of uprooting, especially at higher altitudes where it manifests greater sensitivity to cold winds and snowfall compared to Calabrian pine.

The soil was prepared using steps separated at a 2-m distance; the trees were placed 1.5 m apart along each step. The initial density was about 2,000 trees per hectare. The planting stock consisted of 4-year-old bare-root seedlings.

Reforestation of European chestnut and Turkey oak

Chestnut trees were planted under favorable pedological conditions and in areas with moderate inclination of the slopes, at an altitude from 900 m to 1,200 m a.s.l. The plantations date back to the period between 1957 and 1960 and were performed on soil with 40 x 40 x 40-cm holes and a planting layout of either 1.5 x 1.5 m or 2 x 2 m. In some areas, the trees were placed 1 m apart on ground prepared at 6-m–wide steps and along the steps. The planting stock consisted of 1-year-old seedlings. In 1985, the plantation with the greatest extension underwent coppice treatment.

Turkey oak was planted in three distinct areas at an altitude from 1,000 m to 1,200 m a.s.l. Reforestation was mainly performed using 2 x 2-m holes in which two acorns were placed; in some areas, reforestation was carried out by sowing on land prepared for pitches, which were opened along level curves and placed at 2-m distances.

Study methods

The study was carried out through: *(i)* an analysis of historical land use (before the intervention, in 1957 and 2013); *(ii)* the delimitation of the reforested areas and identification of the species used along with stand age; *(iii)* an update to 2013 of the tree growth data recorded in 1995; and *(iv)* an estimation of biomass, carbon stock and their temporal dynamics (1958-1995; 1995-2013).

The reference data for historical land use analysis were elaborated thanks to information from the Regulatory Plan for Calabria (Cassa per il Mezzogiorno 1957). The information concerning land use up to current events was obtained starting from the Corine Land Cover (CLC) 2006 map, supplemented with other data derived through the interpretation of aerial photos from 2013 (http://www.bing.com/maps/; http://mvexel.dev.openstreetmap.org/bing/). The areas of the CLC categories "temporary crops associated with permanent crops" and "crop systems and complex particles" were compared with those of the arable crops of the 1957 legend, while the areas of the permanent lawns from the CLC were compared with those of meadows and pastures in the 1957 legend (Cassa per il Mezzogiorno 1957).

The delimitation of the reforested areas was performed by interpreting the aerial photos of 2013; these were compared to the same mapped in 1995 (Pignataro 1996, 1997) and verified by ground controls. On this basis, the reforestation map was elaborated according to tree species and stand age.

The growth data were updated to 2013 by repeated surveys in the same sampling areas as those used in 1995. The surveys were carried out in 60 circular plots of different size (from 314 to 1,200 m^2, according to stand density) distributed among the reforestation stands based on species, age, density, and slope morphology: Calabrian pine (50 plots), Douglas fir (2 plots), Turkey oak (2 plots), mixed Calabrian pine and Douglas fir (2 plots), and European chestnut coppices (4 plots).

All trees in the plots were callipered (with a minimum diameter threshold of 5 cm), and a subsample (10%) of tree heights were measured. The Italian National Forest Inventory (IFNC 2009) equations were applied to estimate stand volume and above-ground biomass. To estimate below-ground biomass the following equation was used (Galvagni et al. 2006):

$$BGB_{\%} = 2,258 * Age^{0,662} * G^{0,281} * Density^{-0,152}$$

where *BGB%* is the percentage of below-ground biomass compared to above-ground biomass; *Age* is stand (years); *G* represents the stand basal area (m^2 ha^{-1}); and *Density* is the density of tree stems (No. ha^{-1}). The stored carbon (C stock) was calculated by multiplying the biomass by a conversion factor of 0.50 (Pregitzer and Euskirchen 2004).

Results

Dynamics of land use and reforestation

The forest area of the study site is defined as mountainous (above 300 m) and in 1957 covered 1,870 hectares of land; 65% of this area was coppice woods. The agricultural area in the same context consisted of 5,095 hectares and landslide areas covered 300 hectares. A comparison of these data with those of 2013 shows that the forest area increased slightly more than 3,200 hectares over a period of 57 years, covering 70% of the basin's territory. The increment recorded was due to reforestation (by about 64%) and secondary succession caused by abandonment of agricultural land (36%); such land was not considered for reforestation interventions owing to the favorable morphological conditions (moderate inclination of the slopes). However, due to the exodus of part of the population from these territories, the land was no longer cultivated.

Changes in land use during the examined period (1957-2013) (Fig. 2) confirm that reforestation was mainly performed on grassland and land used for agricultural purposes. Steep slopes were affected, with very eroded and poor soils due to degradation; the agricultural and grassland areas decreased by 94% and 91%, respectively.

(insert Fig. 2 here)

In 2013, the total reforested area was about 2,050 hectares (Fig. 3), including landslide areas, with Calabrian pine covering 78% of the area (Fig. 4).

(insert Fig. 3 here)

(insert Fig. 4 here)

Reforestation accounted for about 30% of the total area and approximately 41% of the forest area in the basin. As for the value reported in the literature for arable land and pasture in the first 30 cm of soil, equal to 56 Mg ha^{-1} (Brenna et al. 2013), and the relative area present in the study area in 1957 (2,180 ha), the quantities of carbon stock were approximately 122,000 Mg.

Biometric analyses and quantity of carbon

Pure reforestation of Calabrian pine

- Data referring to 1995

In 1995, the Calabrian pine stands ranged from 21 to 40 years of age (Tab. 1). Stand density was high throughout almost the entire forest; on average, the number of trees per hectare was about 1,649 ± 270 SD (standard deviation). The differences found at the same stand age and in the absence of thinning confirm the high initial stand density. The average wood volume was 640 m^3 ha^{-1} ± 187 m^3 ha^{-1}. The values of mean annual increment (MAI) of forest stand volume were between 11 and 28 m^3 ha^{-1} $year^{-1}$.

(insert Table1 here)

The distribution of trees in diameter classes revealed a high number in the lower diametric classes; the slenderness ratio (h/d) was higher than 100 in almost all stands. These conditions had a negative impact on the mechanical resistance of the trees during particularly heavy snowfalls with several trees crashing under the load of snow, which did not occur where thinning was performed. In areas that were not spaced out, however, an accumulation of easily ignitable dry biomass was found, which made a portion of these tree populations particularly vulnerable to fires.

The average above-ground biomass was 268 Mg ha^{-1} (± 79 SD), while the average below-ground biomass was about 67 Mg ha^{-1} (± 24 SD). The amount of carbon stocked in Calabrian pine stands was on average about 167 Mg ha^{-1}. For the entire area reforested with Calabrian pine (1,606 ha), the carbon stock was approximately 268,441 Mg.

- Data referring to 2013

Considering a mean age of about 53 years for the whole area, we found that the stands under study were able to store an average quantity of carbon equal to 248 Mg ha^{-1} (Tab. 2). Accounting for the entire area of Calabrian pine, the carbon stock was 398,585 tons. On average, the ratio between below-ground and above-ground biomass was 0.37 (0.26 in 1995).

(insert Table 2 here)

- Thinned stands

In the thinned areas (C1, D1, E1, E2, F1), thinning was mostly carried out in 2000 and, secondarily, in 2010 and 2012, on a total of 567 hectares equal to 35% of the entire reforested pine area. The interventions were defined as low-to-moderate selective thinning, depending on stand density; thinning intensity is shown in Table 3. An average of 819 trees per hectare were cut with an amount of carbon removed equal to approximately 13 Mg ha^{-1}, not considering the root systems of the cut trees.

(insert Table 3 here)

In 2013, the average number of trees was 876 per hectare, with a total biomass (above- and below-ground) averaging 332 Mg ha^{-1}, equivalent to 180 Mg ha^{-1} of carbon stock (Tab. 2). The amount of carbon stored by these stands after 13 years abundantly exceeded the amount removed by thinning. For the thinning procedures carried out in 2010 and 2012, there was a decrease in carbon values that had not been recovered due to the short time interval (Tab. 3).

- Unthinned stands

In 2013, the average number of trees was 1357 per hectare (± 300 SD) in the unthinned stands (A, B, C2, D2, F2 – 1,039 ha). In these stands, natural mortality was on average 360 trees per hectare compared to the number of trees counted 18 years earlier (in 1995). The total biomass (below- and above-ground) ranged from approximately 393 to 686 Mg ha^{-1}, with an average of 569 Mg ha^{-1} (Fig. 5). The average carbon stock in these stands was 284 Mg ha^{-1}, with an overall carbon increment of 144 Mg ha^{-1}, equal to an average of 7.98 Mg ha^{-1} year^{-1} compared with the carbon stock in 1995.

(insert Fig. 5 here)

Reforestation of Calabrian pine mixed with Douglas fir

Both species account for approximately 5% of the total reforested area. In 1995, the two populations were aged 21 and 35 years, respectively, with a particularly high density of

Douglas fir. In the unthinned younger stands, density was equal to 1,556 trees per hectare (88% Calabrian pine and 12% Douglas fir) and remained stable during the period under observation. The quantity of carbon stock was 90 Mg ha^{-1} in 1995 and 253 Mg ha^{-1} in 2013, with an increment of 9.0 Mg ha^{-1} $year^{-1}$. In 2000, the 35-year-old stands were thinned out using a low-grade selective intervention (about 20% of the removed basal area), which resulted in the elimination of 34 Mg ha^{-1} of carbon from a total of 167 Mg ha^{-1}. In the subsequent 13 years, these stands re-established quantities of carbon that were considerably higher than in the thinned stands, resulting in a carbon stock of 196 Mg ha^{-1}. The mean increment of 93.2 Mg ha^{-1} of carbon was equivalent to 7.2 Mg ha^{-1} $year^{-1}$ (Tab. 4a and b).

(insert Table 4a and b here)

Reforestation of Douglas fir

Douglas fir stands represent 5% of the total reforested area. In 1995, the age of the stands ranged from 21 to 34 years. On average, the density was 1,305 trees per hectare with a quantity of carbon stock equal to 170 Mg ha^{-1} (Tab. 4a). In 2000, the older stands underwent thinning with a strong selective intervention which reduced the number of trees by 55%, corresponding to about 25% of the basal area. The eliminated carbon was equal to 31.3 Mg ha^{-1} (Tab. 5). In 2013, the density was 634 trees per hectare with a total quantity of 257 Mg ha^{-1} of carbon stock; the increment was 125 Mg ha^{-1}, equal to 9.61 Mg ha^{-1} $year^{-1}$ (Tab. 4b). The density of the unthinned area (in 2013) was 1,401 trees per hectare, with a total quantity of carbon stock equal to 408 Mg ha^{-1}. The 18-year recorded increment was 241 Mg ha^{-1}, equal to a value of 13.4 Mg ha^{-1} $year^{-1}$ (Tab. 4b).

(insert Table 5 here)

Reforestation of Turkey oak

Reforestation of Turkey oak covered a total of 40 hectares. In 1995, the age of these reforested stands was 25 years. The density was 2,803 trees per hectare, with a total carbon stock of 72 Mg ha^{-1}. In 2013, tree density had slightly decreased (Tab.4a and b) and was attributed to natural mortality. Total carbon stock was 147 Mg ha^{-1}, with an increment of 75 Mg ha^{-1} equal to 4.15 Mg ha^{-1} year^{-1}.

European Chestnut cuttings

Chestnut was planted on an area equal to 8% (178 ha) of the total reforested area. Sixty-five percent of this area was coppiced in 1985; the 1995 data of 10-year-old shoots (Tab. 4a) showed an average density of 1815 stumps per hectare, with an average of four shoots per stump. Total carbon stock was 29 Mg ha^{-1}. The survey was repeated in 2013 (Tab. 4b). A mortality of about 100 stumps per hectare and an average density of 1.7 live shoots per stump were assessed. The total carbon stock was 137 Mg ha^{-1}, with an increment of 108 Mg ha^{-1} equal to 6.01 Mg ha^{-1} year^{-1}.

Discussion

The reforestation of former agricultural land results in significant increments of stored carbon. Several studies have reported that significant amounts of carbon can be sequestered by both forest stands and soil through the adoption of sound management practices (Liao et al. 2010, Ontl et al. 2020). Thus, reforestation is widely recognized as part of the strategy to mitigate greenhouse gases (Laganière et al. 2010, Nave et al. 2019), in compliance with Article 3 of the Kyoto Protocol.

Before becoming forest plantations, the sites investigated herein were arable land and pastures capable of storing a quantity of carbon equal to about 122,000 Mg. After reforestation, carbon values resulted as being quite different: in the Calabrian pine stands, the quantity of carbon in 1995 was about 268,441 Mg in an area totaling 1,606 hectares, equal to 167 Mg ha^{-1}. Considering an average reforestation age of 35 years, these stands stored a quantity of carbon equal to 4.77 Mg ha^{-1} year^{-1} – a very high value considering that the INFC (2009) data estimated carbon sequestration to average 2.45 Mg ha^{-1} year^{-1}. The estimated amount of carbon in 2013 was 248 Mg ha^{-1}, with carbon sequestration equal to 4.67 Mg ha^{-1} year^{-1}. This value doubled compared to that recently reported for the reforestation of 60-year-old black pines in Serbia (Lukić et al. 2015), but was in line with the value reported for black pines by Lal (2005). Douglas fir stands that underwent reforestation and were of the same age as those of Calabrian pine have shown considerably higher carbon sequestration capacities, also due to more favorable soil conditions. For these stands, 313 Mg ha^{-1} of carbon were estimated at the average age of 41 years. Between the first and second investigation, the reforestation of mixed pine and Douglas fir increased carbon uptake by 116% in 18 years.

The quantities of carbon in the stands of deciduous trees were significantly lower. In 1995, chestnut wood coppices averaged the lowest carbon sequestration, with 2.88 Mg ha^{-1} year^{-1} at the age of 10 years. Eighteen years later, carbon stock increased by 375%, with an average of 6.04 Mg ha^{-1} year^{-1}. In the reforestation of Turkey oak over the 18-year period studied, carbon stock increased by slightly more than 100%. The values found are in line with those reported for oak by Lal (2005).

In an interval of 18 years where no thinning was carried out and with the natural mortality of trees ranging from 0% to 18%, the increase in carbon was 64 and 50%, respectively, for the mixed stands of Calabrian pine and Douglas fir and for the pure stands of Calabrian pine and Douglas fir. Instead, where thinning was carried out the increment in carbon was greater than the quantity eliminated by the thinning, varying according to stand age and thinning intensity. In the Calabrian pine stands, averaging 38 years of age, the elimination of about 12 Mg ha^{-1} of carbon (moderate thinning) resulted in almost a double increment of carbon in 13 years. In mixed reforestations of Calabrian pine and Douglas fir, with an average age of 35 years, about 20% of carbon was removed by moderate thinning, while the increment was 47%. In Douglas fir stands (aged 34 years), 16% of carbon was eliminated by thinning, and after 13 years the increment was 49%. Therefore, where thinning was carried out the quantities of carbon eliminated by thinning were reinstated over time in greater quantities.

In similar studies, Navarro et al. (2013) and Jimenez and Navarro (2016) found that thinning treatments clearly reduced annual litterfall. Therefore, thinning treatment causes removal of vegetation cover and a decrease in organic matter. At the same time, the mineralization of soil organic matter (C-sink) increases. Organic matter has a strong influence on soil fertility not only through the substitution of nutrients but also through its effects on other physicochemical properties (Wic Baena et al. 2013).

Considering the age of the stands, the conifers showed a greater uptake of carbon. As for the carbon stock in the above-ground and below-ground biomass, the amount of organic carbon in the soils must also be accounted for. Concerning the reforestation of Calabrian pine, more specifically, reference can be made to the data obtained from research carried out in pedoclimatic contexts similar to those of the study area and in the reforestation of 40-year-old Calabrian pine, where approximately 161 Mg ha^{-1} $year^{-1}$ of carbon sequestration were estimated (Aramini et al. 2007). It follows that, overall, the carbon sequestration of Calabrian pine should have been 409 Mg ha^{-1} in 2013.

If we consider the area in Calabria reforested with Calabrian pine estimated to be about 80,000 hectares, the total potential of CO_2 sequestration would be 120 Mt. Assessing an average age of 53 years, it appears that these reforestations have so far absorbed 2.26 Mt of CO_2 per year. Comparing this figure with that established by the National Inter-Ministerial Committee on Economic Planning, Resolution 123/2002 for aged plants certifiable according to the Kyoto Protocol, equal to 1 Mt of CO_2 per year (Sanesi and Mairota 2010), it appears that the amount of CO_2 sequestered was two-fold greater than that expected in the reforestation of Calabrian pine in the region of Calabria.

Conclusions

The results presented in this study contribute to the awareness of the role of reforestation and forest management in carbon sequestration. In particular, *(i)* reforestation leads to a considerable increment in carbon stock, highlighting the different potentials of the species used (Calabrian pine, Douglas fir, European chestnut, Turkey oak), and *(ii)* thinning exerts a positive effect on carbon sequestration. Furthermore, the differences in carbon stock found between conifers confirm that under difficult soil conditions (largely present in the study area), Calabrian pine manages to maximize its few available resources. For chestnut coppice, this study indicates that rotation time must be lengthened to increase the quantity of stored carbon.

The results obtained prove that silvicultural interventions allow the removal of part of the biomass produced without negatively affecting carbon stock. At the same time, these interventions increase stand stability against abiotic adverse effects; incidentally, they may also enhance the processes of renaturalization and biodiversity. Along with improved superficial hydrology of the slopes and the containment of soil erosion, as confirmed by a number of studies (e.g., Elliot et al. 1999, Hartanto et al. 2003, Altieri et al. 2018), such evidence highlights the multifunctional role of reforestation.

Reforestation and sustainable forms of forest management are powerful strategies for mitigating the effects of climate change through carbon sequestration in biomass and soil

(Chen et al. 2020). The carbon sequestration potential depends on the type of afforestation, the environmental conditions in which it occurs and on the management techniques employed (Fang et al. 2007, Zhiyanski et al. 2016), as was demonstrated herein by a relevant case study under Mediterranean conditions. In general, reforestation can express the maximum potential of carbon stock, especially if performed on formerly cultivated land (Magnani et al. 2005, Munoz-Rojas et al. 2012).

Stand management also plays a pivotal role in determining the amount of carbon (carbon stock) at a defined moment and in defining the budgets (carbon budget) between absorption and greenhouse gas emissions in a specific time interval. This is done by estimating the difference between stock increments and losses related to silvicultural interventions (as demonstrated in this study), or fires, or biotic and abiotic adverse conditions.

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Table 1 - Reforestation of Calabrian pine: dendrometric characteristics and stored carbon in stands, whether or not subject to thinning (situation at the year 1995). Crop treatments: T: thinning; NT: No thinning; Dbh: average diameter at breast height; H: estimated height; h/d: height/diameter ratio; Vol: Wood Volume; MAI: Mean annual increment of wood volume; AGB: above-ground biomass; BGB: below-ground biomass; C stock: carbon stocked.

Stand Group	Crop treatment	Stand Age (years)	Number of trees ha^{-1}	Dbh (cm)	H (m)	h/d	V (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	AGB (Mg ha^{-1})	BGB (Mg ha^{-1})	C stock (Mg ha^{-1})
C1	T	35	1,992	17.0	22.5	132	513	14.6	213	47	130
D1	T	36	1,529	26.3	24.2	92	995	27.6	417	115	266
E1	T	38	1,557	22.6	23.2	103	723	19	303	79	191
E2	T	38	1,486	22.9	23.3	102	710	18.7	297	78	188
F1	T	40	1,913	20.8	22.6	109	733	18.3	306	81	194
A	NT	21	1,340	19.4	22.1	114	437	20.8	182	29	106
B	NT	33	1,288	20.6	16.4	79	355	10.7	148	33	90
C2	NT	35	2,089	20.3	22.5	111	764	21.8	319	78	199
D2	NT	36	1,669	21.3	16.5	77	493	13.7	206	51	128
F2	NT	40	1,626	21.6	22.8	106	679	17	284	76	180
	MEAN	35	1,649	21.5	21.6	103	640	18	268	67	167

Table 2 - Reforestation of Calabrian pine: dendrometric characteristics and stored carbon in stands, whether or not subject to thinning (situation at the year 2013). Crop treatments: T: thinning; NT: No thinning; Dbh: average diameter at breast height; H: estimated height; h/d: height/diameter ratio; Vol: Wood Volume; MAI: Mean annual increment of wood volume; AGB: above-ground biomass; BGB: below-ground biomass; C stock: carbon stocked.

Stand Group	Crop treatment	Stand Age (years)	Number of trees ha^{-1}	Dbh (cm)	H (m)	h/d	V (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	AGB (Mg ha^{-1})	BGB (Mg ha^{-1})	C stock (Mg ha^{-1})
C1	2000	53	908	26,5	24,3	92	604	11,4	253	85	172
D1	2012	54	828	32,6	25,7	79	881	16,3	370	139	264
E1	2000	56	801	33,3	25,9	78	893	16,0	375	145	266
E2	2010	56	1,019	27,3	24,5	90	723	12,9	303	108	212
F1	2012	58	764	26,2	24,2	92	495	8,5	208	71	145
A	NT	39	1,019	27,4	24,5	89	731	18,7	307	86	196
B	NT	51	1,066	30,5	25,2	83	972	19,1	408	146	277
C2	NT	53	1,698	25,6	24,1	94	1,042	19,7	437	155	296
D2	NT	54	1,539	28,3	24,7	87	1,188	22,0	499	187	343
F2	NT	58	1,465	27,6	24,6	89	1,065	18,4	447	172	309
	MEAN	53	1,111	28,5	24,8	87	859	16,3	361	129	248

Table 3 - Reforestation of Calabrian pine: dendrometric characteristics and stored carbon: a) Before thinning; b) Thinning; c) After thinning. Dbh: average diameter at breast height; H: estimated height; h/d: height/diameter ratio; Vol: Wood Volume; MAI: Mean annual increment of wood volume; AGB: above-ground biomass; BGB: below-ground biomass; C stock: carbon stocked.

a) Before thinning										
Stand Group	Stand Age (years)	Year thinning	Number of trees ha^{-1}	Dbh (cm)	H (m)	h/d	V (m^3 ha^{-1})	AGB (Mg ha^{-1})	BGB (Mg ha^{-1})	C stock (Mg ha^{-1})
C1	35	2000	1,992	18,2	21,7	119	563	235	25	130
E1	38	2000	1,557	24,1	23,6	98	831	348	28	188
E2	38	2010	1,486	25,7	24,1	94	925	388	29	208
F1	40	2012	1,913	23,2	23,4	101	943	395	28	212
D1	36	2012	1,529	29,7	25,1	84	1,313	551	32	291

a) Thinning									b) After thinning			
Stand Group	Year thinning	Number of trees ha^{1}	Dbh (cm)	H (m)	V (m^3 ha^{1})	h/d	AGB (Mg ha^{1})	C stock (Mg ha^{1})	Number of trees ha^{1}	V (m^3 ha^{1})	AGB (Mg ha^{1})	C stock (Mg ha^{1})
C1	2000	1,084	9,5	17,2	72	181	29	14	908	490	205	115
E1	2000	695	15,3	20,5	132	134	55	27	862	699	293	161
E2	2010	467	17,8	21,5	127	121	52	26	1,019	797	335	182
F1	2012	1,149	11,6	18,6	131	66	48	24	764	811	346	187
D1	2012	701	17,0	21,2	199	125	70	35	828	1,113	480	256

Table 4a – Reforestations of different tree species: dendrometric characteristics and stored carbon in stands, whether or not subject to thinning. Crop treatments: T: thinning; NT: Not thinning; Dbh: average diameter at breast height; H: estimated height; h/d: height/diameter ratio; Vol: Wood Volume; MAI: Mean annual increment of wood volume; AGB: above-ground biomass; BGB: below-ground biomass; C: carbon stored.

a) situation at the year 1995

Species	Stand Group	Crop treatment	Stand age (years)	Species	Number of trees ha^{-1}	Dbh (cm)	H (m)	h/d	V tot (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	AGB (Mg ha^{-1})	BGB (Mg ha^{-1})	C stock (Mg ha^{-1})
Calabrian pine mixed Douglas fir	G1	T	35	Calabrian pine	1,850	18,6	21,8	117	338,3	9,7	229	52	140
				Douglas Fir	288	11,6	8,9	77	20,8	0,6	9	1	5
				Total	2,138				359,1		238	53	146
	G2	NT	21	Calabrian pine	1,372	16,3	20,9	128	195,4	9,3	126	18	73
				Douglas Fir	184	20,1	22,4	111	44,5	2,1	33	4	19
				Total	1,556				34,6	239,9	159	22	90
Douglas fir	H1	NT	21		1,722	18,5	24,8	134	352,5	16,8	288	46	167
	H2	NT	25		775	25,9	29,8	115	319,2	12,8	281	55	168
	H3	T	34		1,417	19,9	26,1	131	334,9	9,9	280	62	171
Oak	I	NT	25		2,803	11,4	11,2	99	219,8	8,8	126	18	72
Chestnut	L	NT	10		6,975*	5,7	6,2	108	121,8	12,2	54	3	29

*1,815 ha^{-1} stumps

Table 4 b – Reforestation of different tree species: dendrometric characteristics and stored carbon in stands, whether or not subject to thinning. Dbh: average diameter at breast height; H*:* estimated height; h/d*:* height/diameter ratio; Vol: Wood Volume; MAI: Mean annual increment of wood volume; AGB: above-ground biomass; BGB: below-ground biomass; C: carbon stored.

b) situation at the year 2013

Species	Stand Group	Year of thinning	Stand age (years)	Species	Number of trees ha^{-1}	Dbh (cm)	H (m)	h/d	V tot (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	AGB (Mg)ha^{-1}	BGB (Mg)ha^{-1}	C stock (Mg)ha^{-1}
Calabrian pine mixed Douglas fir	G1	2000	53	Calabrian pine	1,019	29,0	24,9	85,8	523	9,9	349		174
				Douglas fir	191	19,2	25,4	132,7	41	0,8	34		21
				Total	1,210				565		384		196
	G2		39	Calabrian pine	1,369	25,6	24,0	94,0	563	14,4	351	98	225
				Douglas fir	191	23,2	23,4	100,7	66	1,7	46	9	28
				Total	1,560				629		398	108	253
Douglas fir	H1		39		1,401	28,6	30,7	107,3	707	18,1	628	189	408
	H2		43		732	33,0	31,6	95,7	495	11,5	441	104	273
	H3	2000	52		634	38,2	32,6	85,3	575	11,1	515		257
Oak	I		43		2,516	14,8	13,9	94,2	345	8,0	8	56	147
Chestnut	L		10		2,930*	13,6	17,4	127,8	357	12,8	233	40	137

*1,719 ha^{-1} stumps

Table 5 – Reforestations of Calabrian pine mixed douglas fir and douglas fir of different ages: dendrometric characteristics and stored carbon in stands: a) before thinning out; b) thinning; c) after thinning. Dbh: average diameter at breast height; H*:* estimated height; h/d*:* height/diameter ratio; Vol: Wood Volume; AGB: above-ground biomass; BGB: below-ground biomass; *C*: carbon stored.

a) Before thinning											
Species	**Stand Group**	**Year of thinning**	**Stand age (years)**	**Number of trees ha^{-1}**	**Dbh (cm)**	**H (m)**	**h/d**	**V (m^3 ha^{-1})**	**AGB (Mg ha^{-1})**	**BGB (Mg ha^{-1})**	**C stock (Mg ha^{-1})**
Calabrian pine mixed douglas fir	G1	2000	40	1,812	18,6	21,8	117,6	386	263	59	160
				288	11,6	8,9	76,7	3	11	1	6
				2,100				389	274	61	167
Douglas fir	H3	2000	39	1,405	21,3	25,7	120,9	418	313	74	193

b) Thinning											c) After thinning		
Species	**Stand Group**	**Year of thinning**	**Stand age (years)**	**Number of trees ha^{-1}**	**Dbh (cm)**	**H (m)**	**V (m^3 ha^{-1})**	**AGB (Mg ha^{-1})**	**C stock (Mg ha^{-1})**	**Number of trees ha^{-1}**	**V (m^3 ha^{-1})**	**AGB (Mg ha^{-1})**	**C stock (Mg ha^{-1})**
Calabrian pine mixed douglas fir	G1	2000	40	634	16,8	21,8	64	64	32	1,178	322	199	128
				86	12	8,9	4	3	2	202	2	7	4
				720			64		34	1,380	325	206	133
Douglas fir	H3	2000	39	718	10,7	21,8	63	62	31	687	356	251	162

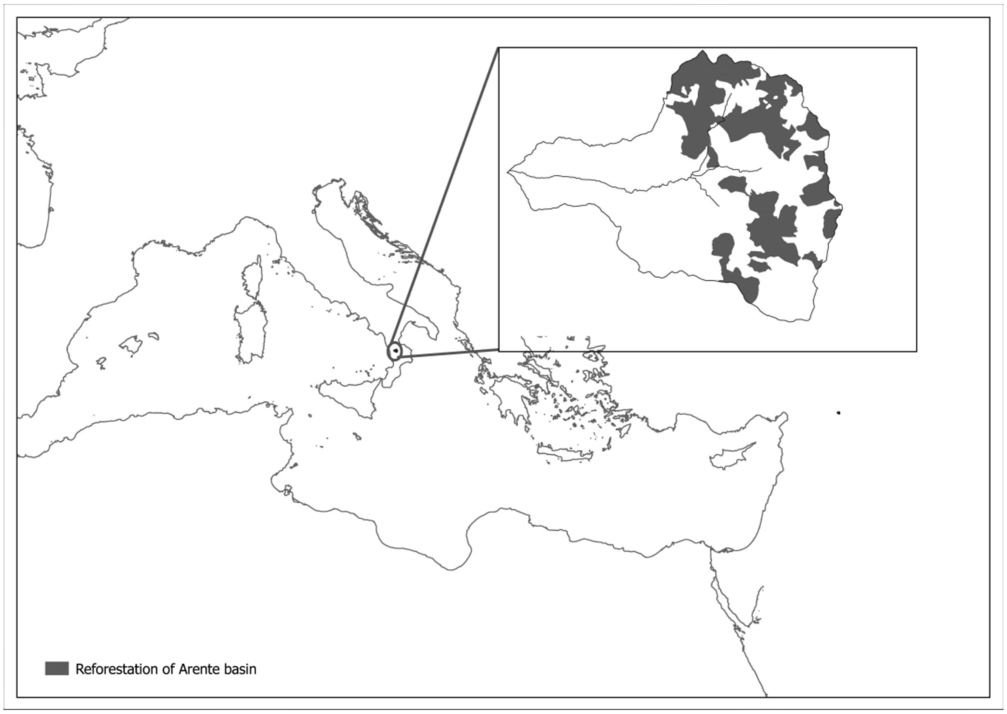
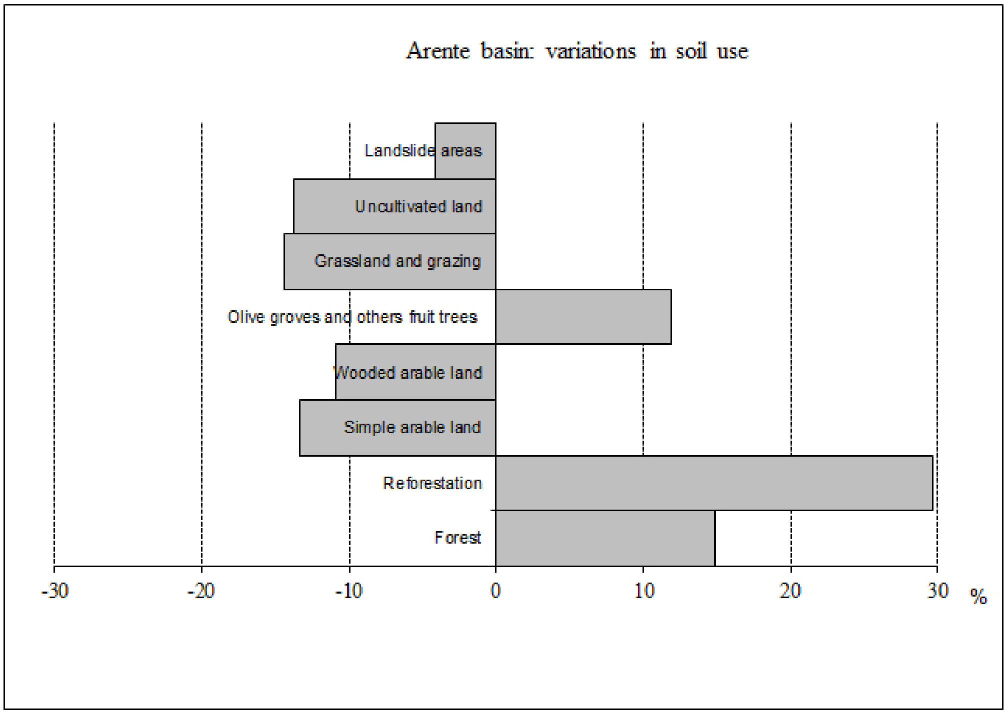


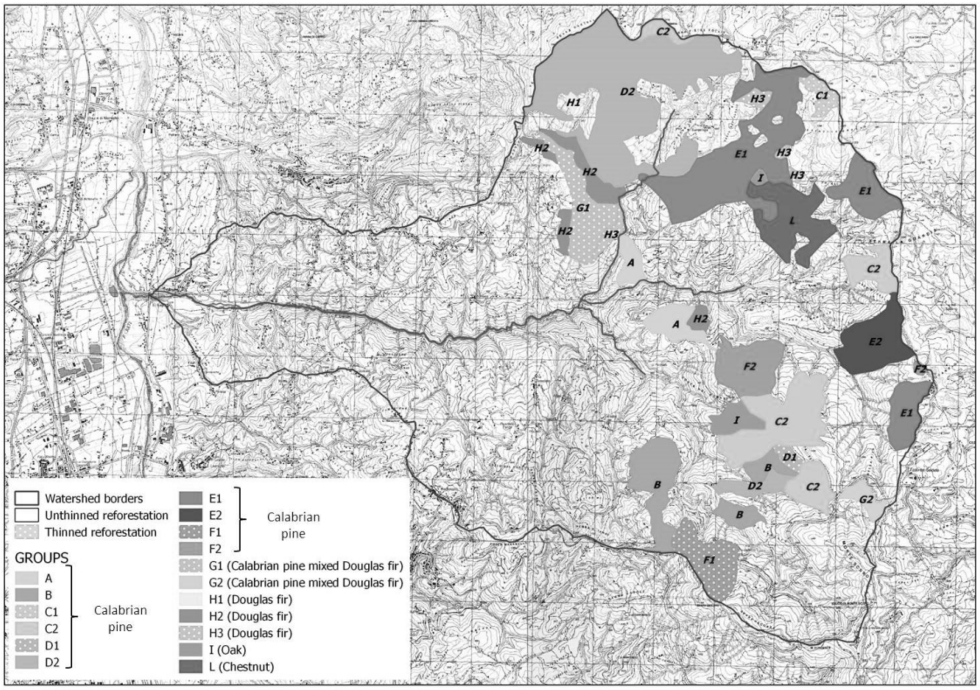
Fig. 1 Study area

1984x1402mm (96 x 96 DPI)



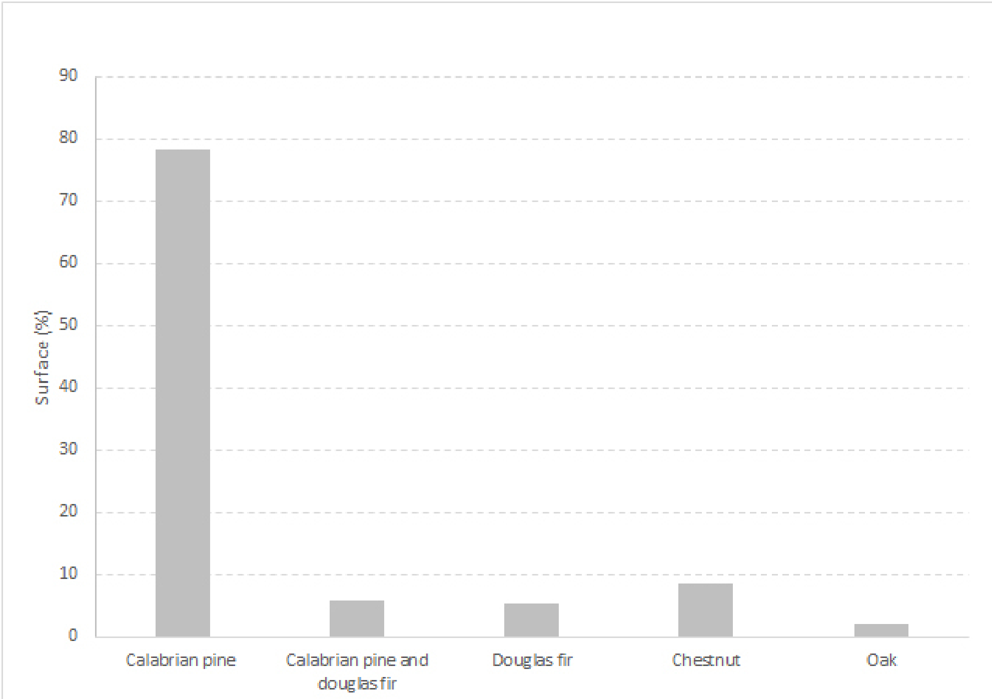
Variations in soil use from 1957 to 2013

108x76mm (150 x 150 DPI)



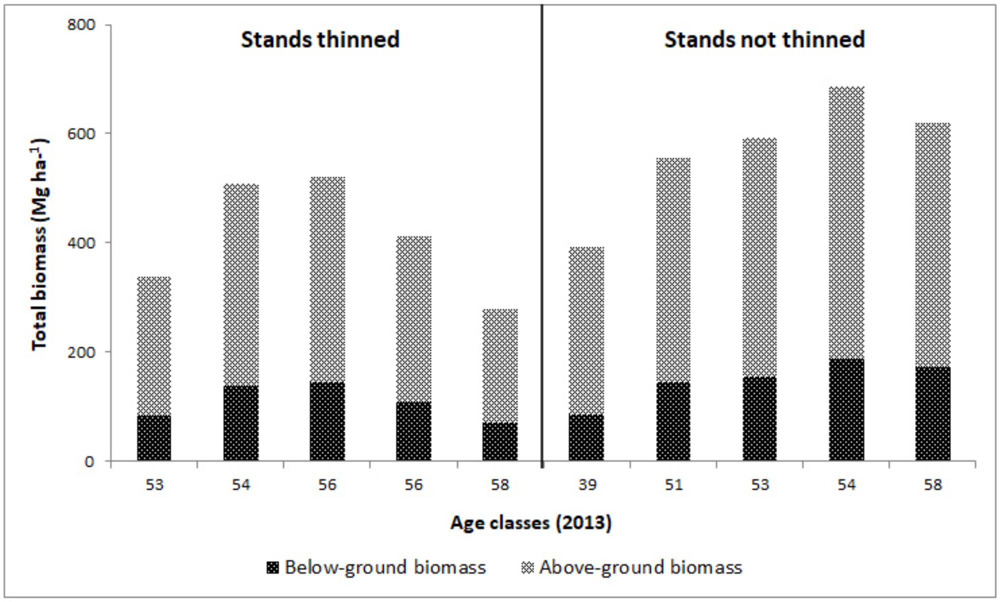
Reforestation distribution in the Arente basin

396x280mm (96 x 96 DPI)



Distribution of reforested surfaces with the various species

108x76mm (150 x 150 DPI)



Total biomass distribution relating to the different ages of the Calabrian pine stands in 2013

62x37mm (300 x 300 DPI)