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State, development and management of monumental chestnut trees (*Castanea sativa* Mill.) in southern Switzerland due to a follow-up inventory 20 years after the first survey

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1. Abstract

In the 2000s, the first inventory of monumental chestnut trees in Ticino was carried out. Twenty years later, this research presents a second inventory of monumental chestnut trees based on part of the monumental chestnut trees surveyed by Krebs in the first inventory, thus enabling an analysis of the development of these centuries-old trees that represents a first in this field. In more detail, the goals of this study are to gain an understanding of the current state of the monumental chestnut trees in the upper valleys of Canton Ticino (Leventina, Blenio and Riviera), to identify the development dynamics that have taken place over the last 20 years and to investigate the role of management, in particular in relation to the health of the trees. For this purpose, some attributes were re-measured and new ones were created to better frame the situation surrounding these trees. Some of the attributes were grouped and processed into indexes that were thereafter used to assess the current situation of health, stability, competition and the degree of management of the monumental chestnut trees and the surrounding area. The findings report a general deterioration in the health condition of the monumental chestnut trees and in the time period between the two inventories 19 out of 101 individuals died, most of them from natural causes. The deceased trees showed common characteristics which could be used as predictors of an imminent death and/or structural failure. To date, trees are characterized by weakened structural compartments. Both stability and health are strongly influenced by the degree of competition suffered by the tree and the environmental conditions to which it is subjected. The degree of management of the chestnut forest in which the surveyed specimen grows was influenced by the slope of the terrain and the proximity to built-up areas. The general degree of management of the tree and its surroundings seems resulted to influence the stability and health of the monumental chestnut trees in the study area, thus emphasizing the importance of management in the conservation of this natural and cultural heritage.

2. Acknowledgment

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3. Introduction and research questions

The attention and attraction to extraordinary natural phenomena and thus to monumental trees has been a characteristic feature of human cultures for millennia (Krebs 2006; Krebs et al. 2014). There are indeed plenty of ancient Roman and Greek texts that demonstrate the importance of the relationship between humans and arboreal prodigies.

The close connection between human civilisation and arboreal wonders has also manifested itself at our latitudes, as witnessed by the rich presence of monumental specimens in the valleys of the southern Swiss Alps (Krebs et al. 2007). Brought into the region during the Roman conquest, the chestnut tree immediately took centre stage in the mountainous zones of the Insubric region, becoming an essential source of subsistence (Krebs et al. 2015; Krebs, Tinner, and Conedera 2014).

The species was pushed up to more than 1,000 m above sea level, i.e. fully exploiting its ecological range of adaptation. In the meantime, the varietal resources have been greatly expanded in order to diversify the yield and meet the multiple needs of the population at that time.

In the late Middle Ages, chestnut cultivation became a proper socio-economic structure, dictating the rhythm of daily life and employing much of the energy, knowledge and interests of our ancestors (Krebs and Conedera 2015). The chestnut tree (*Castanea sativa Mill.)* gradually became the "arbur", i.e. the tree for excellence, and was frequently employed, protected and manured as a symbolic tree next to dwellings and settlements or as a boundary mark for demarcating land parcels and ownership limits (Krebs, Tinner, and Conedera 2014). In the valleys of the Ticino and other regions of Europe, chestnut cultivation and culture grew in this way hand in hand with human civilisation and became a fundamental and profound element of the collective identity of these populations (Krebs 2006).

The later abandonment of chestnut groves and the practice of chestnut cultivation in favour of more intensive forms of agriculture has left a considerable number of monumental chestnut trees in the Italian part of Switzerland as the only living witnesses of a remote past. A past in which the mutualistic symbiosis between the human species and the "bread tree" reached the climax of its development (Krebs, Tinner, and Conedera 2014). The great longevity of the chestnut tree is more a consequence of the extensive care that was regularly provided to the trees in chestnut orchards than a characteristic of the plant species (Krebs et al. 2021). Therefore, with the abandonment of the groves and the abandonment of arboriculture interventions, an acceleration of the ageing processes and an increase in losses of old chestnut trees have been observed. The widespread neglect of chestnut groves could then cause a sharp decline in the number of monumental chestnut trees (Krebs 2006).

Between 1999 and 2004, 315 monumental chestnut trees were surveyed in southern Switzerland, by using only the circumference of at least 7 metres at 130 cm above the ground as selection criterion (Krebs 2004). The unique longevity of the species *Castanea sativa Mill*., the rarity of the presence of a first systematic inventory and the possibility of its repetition after twenty years, makes it possible to study the evolution of the health conditions of these veteran trees and to answer the following research questions:

1) Q1*: What is the current general health condition of monumental chestnut trees in the upper valleys of Canton Ticino?*
2) Q2: *What are the dynamics and changes that have characterised the last twenty years?*
3) Q3: *What management interventions have monumental chestnut trees undergone? How have they reacted to these interventions?*

To this end, about one hundred monumental chestnut trees inventoried around the year 2000 in the region of the three valleys (Leventina, Blenio and Riviera) were revisited and measured. In addition to the parameters already recorded in the first inventory, new observations were added in order to better describe and assess the evolutionary trends as well as the main environmental and management factors influencing the phytosanitary and developmental conditions of monumental chestnut trees. Although this is a sub-inventory as not all trees in the first inventory were included in this study, it will from now on be referred to as the "second inventory" for convenience.

4. Materials and methods

4.1 Study area

For this study, a sub-area of the Krebs inventory was selected (Fig. 1), which corresponds to the three valleys of the upper Ticino (Leventina, Blenio and Riviera) so as to be able to reassess around one third of the inventoried giant chestnuts and to complete the surveys in the field over a period of 2 to 3 months. From a historical perspective, the three valleys considered coincide with the region commonly known under the name "Tre Valli ambrosiane" (from here on just "Tre Valli"), that is the "Three Valleys" where the official Catholic liturgical rite is the Ambrosian Rite of the Archdiocese of Milan, also called the Milanese Rite. In geomorphology, a valley is defined as a hollow form of the land consisting of two hillsides often crossed at the bottom by a watercourse (Toniolo 1937). In this research the valleys considered are crossed by the Ticino river for the Leventina and Riviera valleys and by the Brenno river for the Blenio valley. The Brenno is an affluent of the Ticino River and in its terminal section it marks the border between Leventina and Riviera. In this research, the Leventina, Blenio and Riviera valleys are defined by considering both their geomorphological characteristics and the administrative-political units. In the specific case, we defined the Riviera valley as the entire segment of the valley of the Ticino river from the confluence with the Brenno river to the confluence with the Moesa river, which corresponds to the Riviera administrative district merged and enlarged with the municipal territories of Claro, Moleno, Preonzo and Gnosca. Thus, the definition of the landscape districts defined by Canton Ticino in *sheet P2* of the Master Plan is adopted (Repubblica e Cantone Ticino 2012). The choice of this definition coincides with the division adopted by Krebs during his inventory (Krebs 2004).

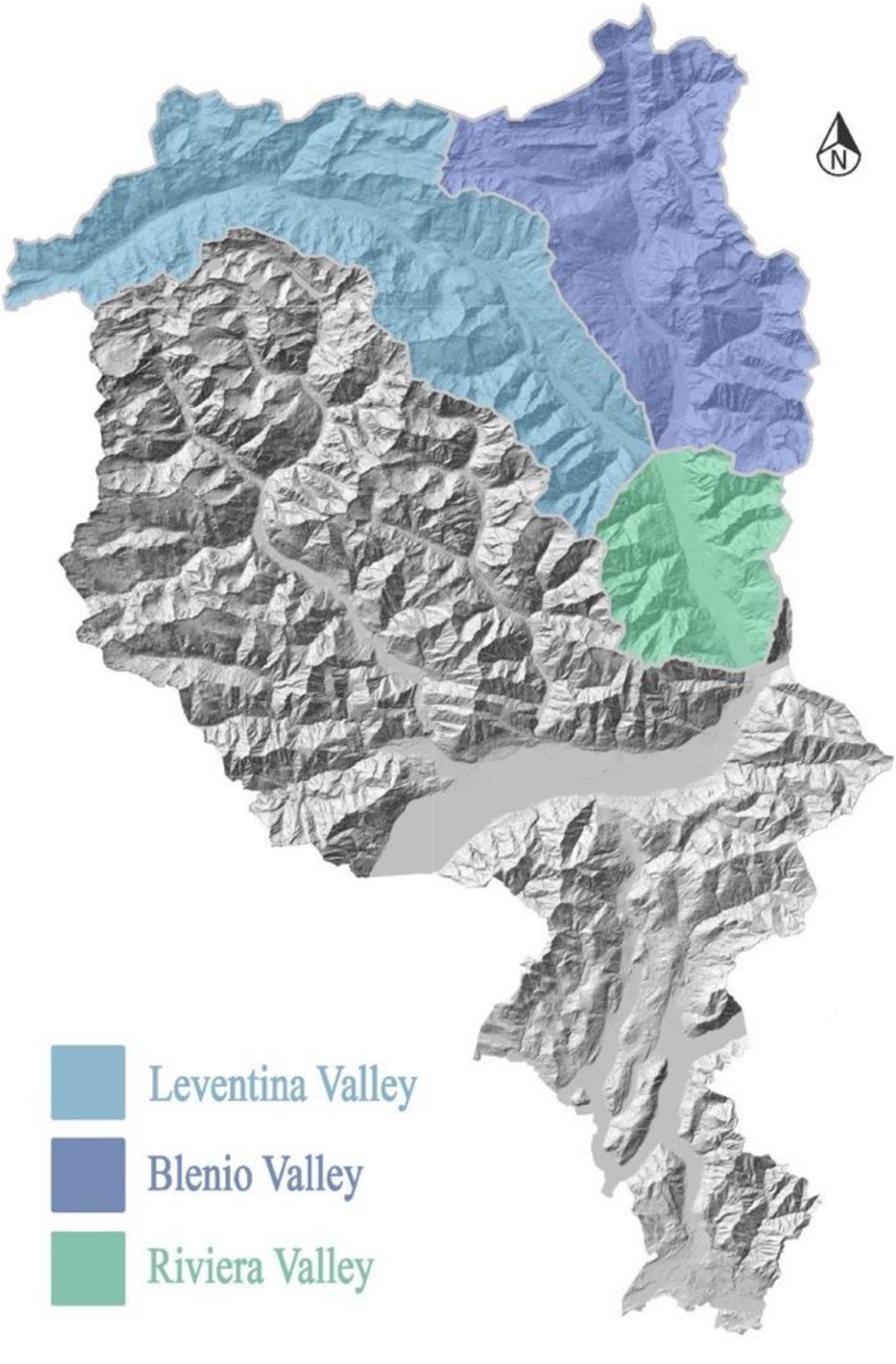

Figure 1: Canton Ticino elevation profile map showing the study area divided into the 3 valleys: Leventina (light blue), Blenio (dark blue) and Riviera (sea green).

The area of the three valleys is approximately 103'813 ha, corresponding to 37% of the total area of the Italian-speaking Canton. The Leventina valley is the widest in the study area, representing the 46% of the total area of the three valleys is occupied by this valley, followed by the Riviera valley with

35% and finally the Blenio valley with 18%. The distribution range of the chestnut tree convers only the lower part of the Tre Valli territories mainly below 1'000 m above sea level, but a large part of the study area is above the upper limit. Thus the area available for the chestnut tree is reduced to 18% of the total area of the Tre Valli, which corresponds to about 18'599 ha. Of this suitable area 33% is in the Leventina valley, 27% in the Blenio valley and 40% in the Riviera.

Looking closer at the situation, not all the altitude range is available for the "*bread tree*", as the valley floor is often occupied by residential, industrial, agricultural and other areas. The altitude range in which the chestnut tree can be therefore found ranges from about 300 to 900 m above sea level; this reduces the area available for the chestnut tree in the three valleys to about 10'543 ha, of which 3'500 ha (33%) in the Leventina Valley, about 3’300 ha (32%) in the “*Valle del sole*” (Blenio Valley) and about 3'700 ha (35%) in the Riviera Valley.

There is no universal definition of "chestnut orchard" (*selva castanile*), as it a particular case of fruit tree plantation or stand which can have highly variable characteristics. For this reason, it is complicated and hard to obtain precise information on the area of chestnut orchards. Nevertheless, there are some national maps which indicate their occurrence. An example is given by the *Siegfried* maps of 1915-1935 where the area marked as “*selva castanile”* in Ticino is 6'353.4 ha, of which about 1'355.4 ha in the three valleys subject to this study (Krebs 2021). About 40% of this area (541.8 ha) is located in the Leventina valley while the Blenio and Riviera valleys have 319.52 ha and 493.12 ha respectively. The total area of chestnut orchards shown on the *Siegfried* maps of this edition is relatively small and the reason is probably the limited demarcation due to the restrictive definition of chestnut orchards ("*pure*" chestnut orchard) applied in this edition. In the 1959 *Siegfried* map there are five categories describing areas with sweet chestnut tree as dominant, co-dominant and secondary species. The total area of these categories in Ticino amounts to 8'552.5 hectares of which 37% in the Tre Valli. About one third of this territory is distributed in each of the three valleys; the Leventina valley hosts 1'029 ha, while the Blenio valley and the Riviera valley contain about 1'167 and 1'004 ha respectively. It can be noted that the Blenio valley has a smaller total area available for chestnut trees than the other two valleys but has a larger surface of areas that can be identified as chestnut orchard. Subsequently it will be learned that despite this data in the Blenio valley the presence of monumental chestnut trees is significantly lower than in the Leventina and Riviera valleys.

The population of the Canton of Ticino in 1850 was 117'759; it subsequently increased, reaching a peak of annual percentage growth (+1.34%) between 1941 and 1970 (Schuler et al. 2002). In 2000, the population stood at 306'846. The Blenio district had 7'687 inhabitants in 1850, the annual percentage population decreased until 1970 and then increased until 2000, reaching a total population of 5'287. The Leventina district, on the other hand, had an annual percentage increase between 1850 and 1880 and between 1941 and 1970, but a yearly percentage decrease between 1880 and 1940. In 2000 the population amounted at 9'502 inhabitants. The fluctuation of the population of Leventina is due to the availability of employment offered by the Gotthard railway projects (Schuler et al. 2002). The population of the Riviera district has almost always increased, reaching in 2000 11'434 inhabitants.

In this master thesis, 101 monumental chestnut trees were re-visited and recorded (see Annex 1 for more details on the percentage of trees surveyed compared to the first inventory in the respective valleys and Fig. 2 for the tree position).

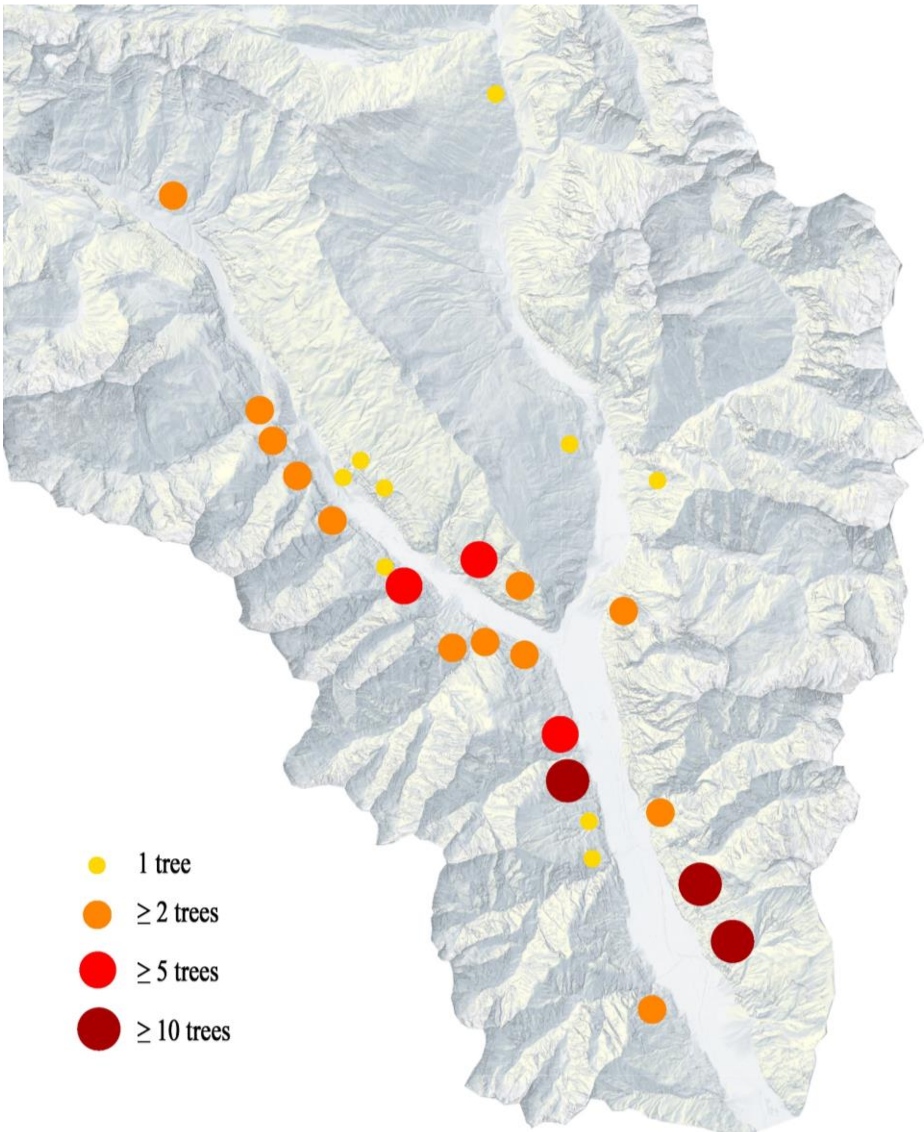

Figure 2: Elevation profile map of the portion of the study area that features monumental chestnut trees. The size and color of the dot represent the number of Chestnut trees present at that site. In order of increasing size: yellow dots represent a single monumental chestnut tree, orange dots represent 2 to 4 monumental chestnut trees, red dots represent 5 to 9 monumental chestnut trees and dark red dots represent a minimum of 10 monumental chestnut trees.

The altitudinal distribution of the monumental chestnut trees in the second inventory (Fig. 3) is characterised by an average of 780 m above sea level and only one monumental chestnut tree exceeding 1'000 m.a.s.l., with a maximum altitude of 1'013 m.a.s.l (locality of Fontané in Leventina). The highest average altitude of the distribution of monumental chestnuts is observed in the Blenio valley at 887 m.a.s.l, followed by the Leventina valley at 815 m.a.s.l and finally the Riviera valley at 741 m.a.s.l..

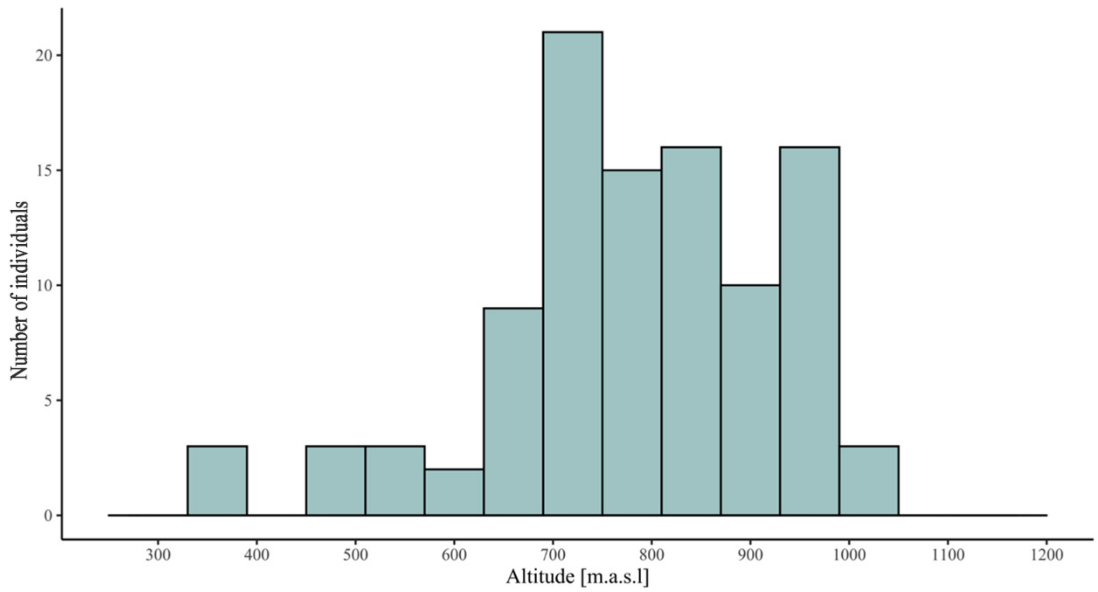

Figure 3: Altitudinal distribution of monumental tree of the second inventory (2021-2022), expressed as the number of individuals per altitudinal range.

4.2 General description of the first inventory

The aim of the first inventory of monumental chestnut trees was to survey the entire population of tree specimens with a trunk circumference of at least seven metres (measured at breast height) in the valleys of southern Switzerland included in the Canton of Ticino and in the Moesa region which cover an area of approximately 3'308 km^2 (Krebs et al. 2015). In order to find them, the exploration area was first reduced by using the chestnut distribution map (IFRF 1959) as a base for the survey and focusing on the 310.7 km^2 representing the distribution range of *Castanea sativa Mill* (Krebs et al. 2007). After consultation with several experts of the territory, the reduced research area was meticulously surveyed and about 350 full days were invested (Krebs et al. 2021). The result was a systematic census of 319 monumental chestnut trees, which are estimated to represent 80-95% of the total population in the swiss regions belonging to the drainage basin of the Ticino river.

The first inventory was conducted between 1999 and 2004 (Fig. 4) and resulted in 305 trees catalogued following the order of census and a provided two-page description sheet each (Krebs 2004). In the first section of the final general information is provided.

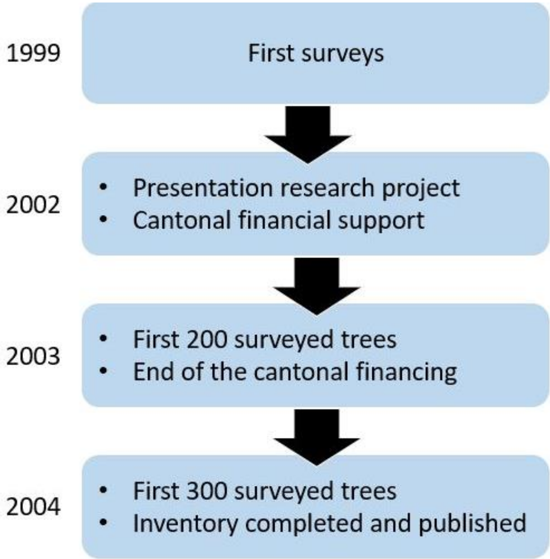

Figure 4: Major steps that led to the development of the first inventory of monumental chestnut trees.

The documentation of the first inventory contains all the other information collected in the field or obtained through GIS. In addition to the measured parameters (cardinal and ordinal attributes) there are various descriptions of the tree, the environment in which the tree is found and, where possible, historical and oral information. A complete description of the parameters as well as the method used to collect them can be found in the documentation concerning the first inventory on pages 54 to 56 under the chapter "*Legenda schede*" (Krebs 2004). A photographic archive of all specimens was also generated during the first inventory. The photographic material was produced with the main objective of replicating future circumference measurements and is therefore rich in detail, especially of the lower part of the trunk.

4.3 Conceptional framework

In this study, available or derived data from the first inventory and data collected during the second inventory were used to conduct the analysis and to create the indices of competition, stability, health and management (Fig. 5). The four indices and statistical analysis enabled the three research questions to be answered, drawing conclusions about the current status of monumental chestnut trees, ongoing trends, and the influence of management on them.

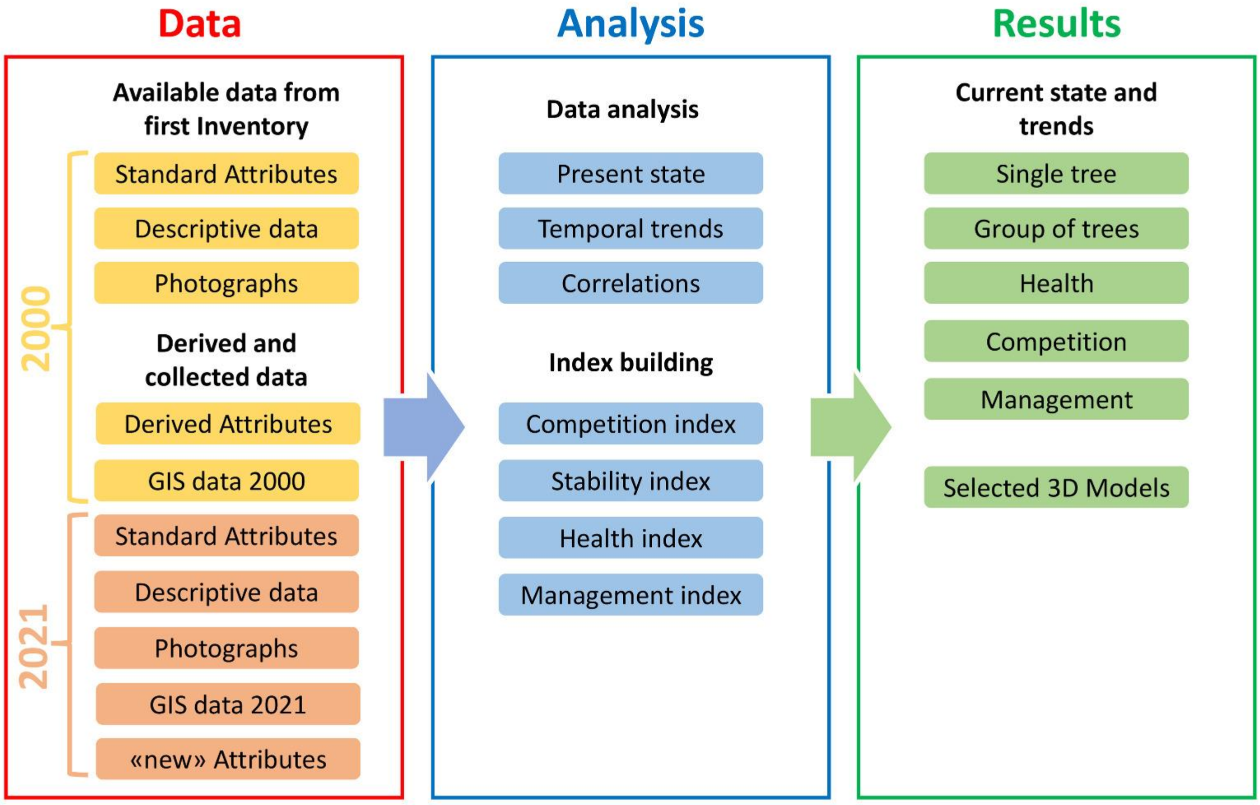

Figure 5: Flowchart representing the research workflow. The first box (red) shows all the data used to answer the research questions, divided in available data from the first inventory and derived and collected data. The data are also divided into data concerning the situation in the 2000s during the first inventory (yellow) and data concerning the situation in 2021 during the second inventory (orange). The available, derived and collected data were then used for statistical analysis and index creation (blue box), which consequently led the results needed to answer the three research questions and achieve the goals of this study.

The data from the first inventory were either already present as a value or were derived through GIS, photographic material or from the descriptive text provided by Krebs in the document he compiled. The data from the second inventory, instead, were collected either in the field or via GIS (Fig. 6). In Annex 2, the source is indicated for each attribute.

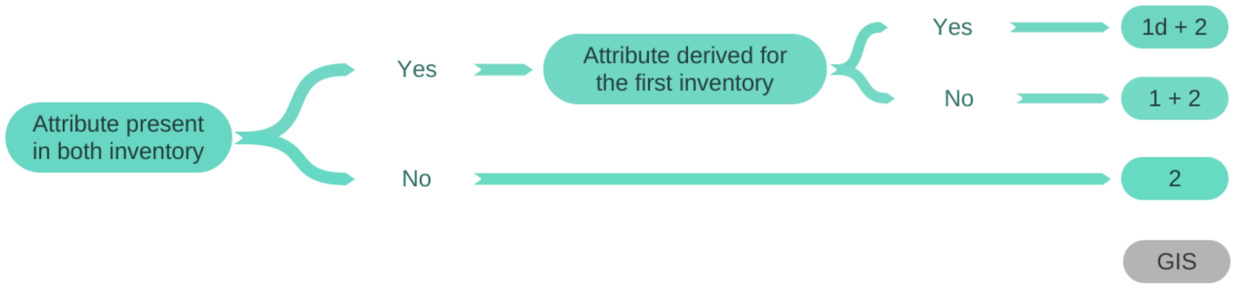

Figure 6: Categorization of attributes according to their origin and data collection process. GIS data are grayed out and are not connected by any arrows since, as they are produced with the use of software they are neither among the data collected in the field nor among those derived.

The search for the answer to the first research question (*Q1*) was based on data from the second inventory, while the answer to the second research question (*Q2*) was based on a comparison between the first and second inventories. For the last research question (*Q3*) the data mainly flowed from the second inventory (management index), but the comparison of attributes required a portion of the data from the first inventory. The construction of indexes within the analysis made use of attributes from the second inventory, they therefore express the current situation and were not used for the *Q2* research question.

4.4 Data explanation

It was decided to divide the volume of data into the following groups.

1) Tree data
2) Geographical and environmental data
3) Competition data
4) Management data

The tree data group includes all those data describing the tree itself (structural compartments, health, stability, presence of nails on the trunk etc.). Data belonging to the geographic and environmental group are those data describing the geographical location of the monumental tree and its environment, such as the coordinates of the tree's location and the degree of rockiness surrounding the tree**.** The data belonging to the competition group includes all the data used to construct the competition index, i.e. information regarding the trees surrounding the analyzed specimen**.** Finally, the management group data are those data that describe the degree of management on and around the tree itself**.**

The attributes present in this study will be explained in the following, each attribute label can take either the number 1 or 2 as the final designation of its name; these numbers indicate whether it belongs to the first inventory (2000 data) or the second (2021 data). Annex 2 contains a complete table of all attributes concerning this study.

4.4.1 Tree data

All attributes belonging to this group can be found in the first part of the table in Annex 2. The attributes presented below concern characteristics of the crown and trunk of the monumental tree, as well as attributes concerning health status, death class and the presence of human accessory signs on the tree or in its immediate vicinity. Some of these attributes were used for the construction of the health and stability index (Fig. 7).

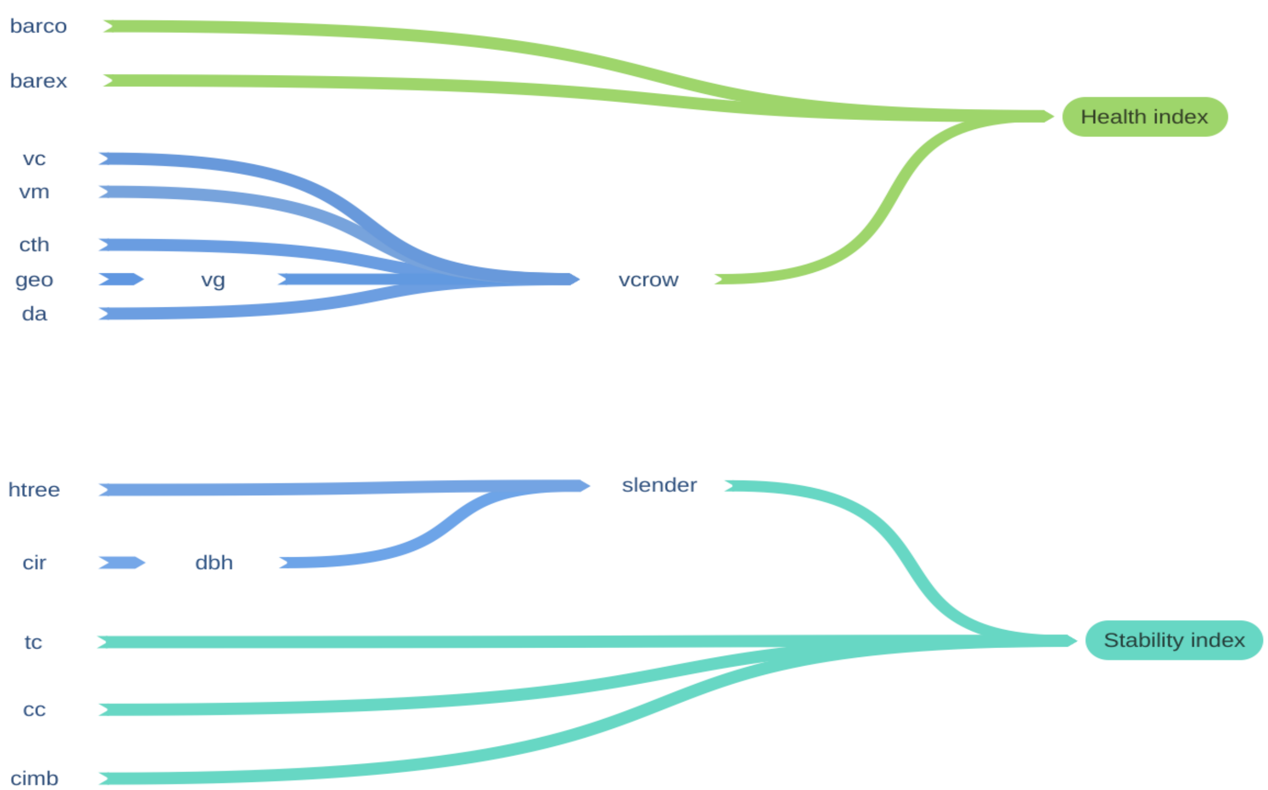

Figure 7: diagram showing the various tree data attributes used to create the health (green) index and stability index (sea green).

Trunk circumference at breast height *(cir)*

The circumference of the trunk in the first survey is measured at an average height of 1.3 m above the ground (e.g., lower on the upstream side of the tree trunk and higher on the downstream side). The tools used to obtain this information are listed below:

- Metric tape measure (centimetric precision)
- Hammer and nail (especially if measuring is done alone)
- Spring clamp

The circumference is determined with a metric tape measure following a measurement plane perpendicular to the axis of the trunk. This plane must be approximately 130 cm above the ground and must provide the minimum circumference value (it must therefore avoid very prominent protuberances). As a first step, the metric rule is positioned on the basis of an initial assessment of the distances from the ground on all sides of the trunk. If the work is carried out individually, a nail and a hammer can be used to hold the measuring tape at the initial position. After an evaluation of the positioning of the measuring tape, its position is adjusted; the metric tape often has to be moved because of branches or large protuberance, which must be avoided in order not to overestimate the circumference. Finally, the measure is validated only after applying sufficient force to both ends of the metric tape measure to ensure that it is well tensioned and follows the shortest path of circumference. Procedures in the event of "*special case*" can be found in Annex 3.

The measurement of the circumference in the second inventory was dictated by the need to follow exactly the same path on the trunk taken during the first inventory so that comparisons would be possible. To do this, the photographs of the first inventory showing the original positioning of the measuring tape on the underside of the trunk were used and, with the help of coloured pins, the points where the measuring tape had passed 20 years previously were marked directly by tapping them into the bark. Afterwards, the measuring tape was positioned along the path marked by the coloured pins. One end of the tape was then hooked onto a nail, while the other end, after having followed the circumference of the trunk, was joined to the first end and fixed with a spring clamp. A first evaluation and comparison of the photographed path of the metric tape on the trunk was then carried out and as a final step the measurement was read by pulling the two ends of the metric tape with force in order to stretch the tape to its maximum. In addition to the circumference, the degree of accuracy of this measurement was noted on a scale of 0 to 4, where 0 indicates the higher level of inaccuracy (i.e., great uncertainty about the correctness and coincidence of positioning) and 4 a perfect passage of the measuring tape through the same positions as in the first inventory.

Diameter at breast height (*dbh*)

The attribute *dbh* is obtained by means of the following mathematical formula:

$$dbh = \frac{cir}{2\pi}$$

Tree height *(htree)*

The vertical height of the tree in the first inventory (*htree1*) was measured using a laser distancing device. The measurement was taken from the collar level downhill to the top of the highest branches supported by the trunk and not arising from adventitious buds of the collar or lateral roots.

In the second inventory a different method was used for the height measurement (*htree2*). The reason for this is the more precise equipment available i.e., the Vertex III instrument and T3 transponder. This is a professional instrument capable of measuring distances with the help of ultrasound and the principles of trigonometry. The instrument itself consists of two components: a transponder (capable of "reflecting" an acoustic signal) which must be fixed at a precise height on the trunk (in this research 1.30 m above the ground) and the vertex, an electronic device which emits ultrasound and is able to calculate the height of the tree using trigonometric principles. The *htree2* measurement was therefore read directly from this measuring tool. In cases where the terrain was inclined, an attempt was made, when possible, to take the measurement along the horizontal line which is parallel to the contour lines and crosses the axis of the trunk. In cases where measurement along the horizontal line was impossible, the measurement was taken along a slope line, but manually correcting the measurement obtained, i.e. taking into account the difference in height between the vertex and the transponder.

Slenderness coefficient (*slender*)

The slenderness coefficient (*slender*) of a tree is defined as the quotient of the tree height (*htree*) and the trunk diameter at 1.30 m above the ground (*dbh*) (Wang et al. 1998).

$$slender = \frac{htree}{dbh}$$

This parameter is often regarded as a measure of tree stability, especially in relation to resistance to wind-induced fall (Mattheck 2007).

Trunk height, crown base height and crown thickness *(htrunk, hcb and cth)*

Trunk height (*htrunk*) is defined here as the distance from the ground up to the saddle of the first bifurcation of the trunk. The height of the base of the crown (*hcb*), regardless of whether it is dead or alive, is defined as the distance from the ground to the first branches that make up the crown starting from the bottom. These branches should not be too far from the crown figure. Therefore, if the first branch met from below is isolated from the homogeneous and continuous structure of the crown, it does not count as a branch for the identification of the crown base. The measurement of these two attributes was performed with the same method and tools used to measure tree height in the second inventory (*htree2*).

The crown thickness (*cth*) was instead calculated as follows:

$$cth = htree - hcb$$

Crown diameter *(d1, d2)* and average crown diameter (*da*)

The diameter of the crown has been measured firstly along its longest axis (*d1*) and secondly following an axis perpendicular to the first one (*d2*), by considering the projection on the ground of these two axes. These measurements were made using a laser distance measuring device (*Leica Disto X3*), which is an improved model compared to the one used by Krebs during the first inventory. The average diameter (*da*), on the other hand, is the result of the sum of the two measurements *d1* and *d2* divided by two.

Geometric figure of the crown *(geo)*

The geometric volume (*geo*) of the crown is defined here as the geometric volume which better fits and describes the crown shape. Ideally it must include all the branches and the empty spaces between them. The geometric volume can be described according to the following solid figures: sphere, ellipsoid, cylinder, cone and paraboloid. This attribute is one of the parameters used to calculate the volume of the crown (Fig. 7). The assignment of the geometric figure to the crown of the analysed trees was carried out in the field by means of observation from a suitable distance in order to have a complete view of the crown.

Missing crown volume *(vm)* and compromised crown volume *(vc)*

The missing crown volume (*vm*) has been defined as the portion (values ranging from 0 to 1) of missing volume in the crown assessed by considering the ratio between the whole of the missing parts (empty volumes) and the whole of the remaining parts (full volumes still well equipped with branches).

The compromised or dead crown volume (*vc*), on the other hand, is defined as the percentage of the remaining crown volume (or of the residual crown branches) which appears compromised, damaged, diseased, dying or dead (values ranging from 0 to 1). Hence as a compromised percentage of the volume resulting from the subtraction of the missing volume from the geometric volume of the crown (*vg* - *vm*).

Both attributes *vm* and *vc* were estimated in the field through meticulous observation of the crown.

Crown volume *(vcrow)*

The volume of the crown was calculated as follows: the geometric volume[1](*vgeo*) was first calculated based on the geometric figure that best describes the crown as a geometric solid (*geo*), from which the volume of the missing crown (*vm*) and the volume of the compromised crown (*vc*) were subsequently subtracted.

The following formula was applied for each specimen:

$$\boldsymbol{vcrow = vgeo * (1 - vm) * (1 - vc)}$$

Hierarchical crown position *(cpos)*

The attribute *cpos1*, which describes by mean of a 0-4 scale (with 0.5 increment) the hierarchical position of the crown in relation to the crowns of the trees surrounding the monumental tree (Tab. 1). In the first inventory it was derived and assessed by means of the wide-angle photographs, i.e. those photographs of the tree shown in full. *Cpos1* was also occasionally mentioned indirectly in the descriptive text of the first inventory, as for example in the record of tree ID24 where it is written in the description: "*... Its crown is only slightly taller than the overgrown brushwood that is growing all around it...*". This description plus the photographs analyzed led, for example, to the assignment of the value 1.5 for the attribute *cpos1* for this specimen.

The hierarchical position of the crown in the second inventory (*cpos2*), on the other hand, was based on the distanced observation of the crown of the monumental tree in comparison with the other crowns around it.

Table 1: Description of the hierarchical crown position scale values (*cpos*).

Value	Description
0	Open grow
1	Dominant crown
2	Co-dominant crown
3	Intermediate crown
4	Suppressed crown

Crown closure *(cclo)*

The crown closure (*cclo*) of tree analysed in relation to the crowns of the other surrounding trees was assessed using a scale of values from 0 to 4 (with increment of 0.5). The minimum value indicates that the crown of the monumental tree is free from other competitor crown, while the intermediate value (2) indicates that the chestnut tree's crown is surrounded on one side and free on the other. Finally, the highest value on this scale indicates a tree whose crown is completely surrounded by the crowns of other trees.

Degree of bark extension *(barex)*

This attribute is an estimate of the degree of bark extension on the lower trunk (50 cm above and below the circumference measurement) of the tree. The values range from 0 to 4 with increment of 0.5. A value of 0 is assigned to a tree with bark absent along the entire circumference while a value of 4 is assigned to a tree with bark covering the entire trunk circumference. The scale is linear and increments of 1 point correspond to an increase in bark coverage by 1/4 of the circumference.

Degree of trunk cavity *(cav)*

The degree of trunk cavity is based on observation of the lower trunk surface, i.e. the surface clearly visible from below (human eye level). Other cavities are often very difficult to detect, especially when the trunk is very high. Values of *cav* varies between 0 and 4, with 0.5 increments. The minimum value indicates a trunk apparently free of cavities, 2 indicates a cavity volume of approximately half of the total cavity (*cav* = 4) and the value 4 represent a huge cavity, where the trunk interior is completely absent; or a trunk with an absent façade as it is completely open, characterized by a residual wall (opposite façade) thin and fragilized by the cavity.

Extent and severity of crown and trunk cracks (*cc* and *tc*)

The attributes *cc* and *tc* represent the extent and severity of cracks on the crown and trunk respectively. Thus, they are not only intended to measure the amount of cracks present in the structures, but also their impact on structural integrity. *tc* and *cc* are measured using a linear gradual scale of values ranging from 0 to 4 with 0.5 increments (Tab. 2).

For the first inventory, the attribute values were derived mainly from the photographic material in Krebs' archive and sometimes also from precise textual descriptions in the annotations of the documentation. It was sometimes difficult to estimate the attribute *cc1* because there were no systematic shots for every angle of the canopy (unlike the photographs of the lower trunk), and the presence of foliage in the crown often obscured the view of the bare branches, and thus the cracks.

In the second inventory, on the other hand, these two attributes were estimated through detailed field observations of trunk and crown, the work being facilitated by the absence of dense foliage.

Table 2: Description of attribute scale values extent and severity of crown crack (*cc*) and trunk cracks (*tc*).

Value	Description extent and severity of crown cracks (*cc*)	Description extent and severity of trunk cracks (*tc*)
0	Apparently no visible cracks in the crown structure	Apparently no cracks on the inferior part of the trunk structure
1	Few, minor cracks on the crown structure	Few, minor cracks on the inferior trunk structure
2	Some areas of the crown structure are characterized by (not too severe) cracks	Some areas of the inferior trunk structure are characterized by (not too severe) cracks
3	Severe cracks on one or more portions of the crown structure	Severe cracks on one or more portions of the inferior trunk structure
4	Severe cracks present on the entire crown structure	Severe cracks present on the entire inferior trunk structure

Bark health condition (*barco*)

The values of *barco* are determined by a linear scale of values ranging from 0 to 4 with 0.5 increments (Tab. 3).

The bark health condition in the first inventory (*barco1*) was assess mainly by means of the photographic material available. Particular attention was paid to the bark colouration and the presence of cracks or detachments from the trunk.

Contrary to the attribute *barco1*, the assessment of *barco2* values was greatly facilitated by the possibility of directly inspecting the degree of attachment of the bark to the trunk. For this purpose, the bark was tapped along the entire circumference of the tree. In this way it was possible to better understand whether the bark was still vital and able to fully perform its functions.

Table 3: Description of bark health condition scale values (*barco*).

Value	Description
0	Very weak bark. Functionality of the bark is not assured
1	Tree bark with weakened and/or partly not intact functionality on most of the trunk
2	Tree bark with some weakened or/and partly not intact functionality
3	Firm and vital tree bark on most of the trunk, only a few signs of weakening.
4	Firm and vital bark with clear signs of full functionality

Imbalance of the crown *(cimb)*

A strongly imbalanced crown can have severe implications for the development of an organism; in general, an important consequence is the elevated risk of branch breakage and failure (Fay 2002). The ordinal attribute estimating crown imbalance is *cimb*. It is intended to describe how the crown of the monumental tree fills the space above the trunk. Specifically, it investigates the symmetries with respect to the central vertical axis (i.e., the trunk) and the degree of balance when considering the distribution of the branches and wood masses. The less homogeneous the distribution of branches and the less symmetrical the tree's crown is, the more unbalanced the crown will be. The values of this attribute are on a linear scale ranging from 0 to 4, with an increment of 0.5. (Tab. 4).

The values in the first inventory were derived from the photographs in the Krebs archive and some annotations in the tree description.

Instead, the values in the second inventory were assigned after a close observation of the crown, in particular, the lengths of the branches in relation to the vertical axis of the tree were taken into account and evaluated.

Table 4: Description of imbalance of the crown scale values (*cimb*).

Value	**Description**
0	Stable, well-distributed and balanced crown
1	Between stable and slightly unstable crown, it is unevenly distributed in space.
2	Slightly unstable and unevenly distributed crown
3	Clear structural imbalance of the crown that could compromise the structure stability of the tree
4	Strong structural imbalance in the crown. Branches not uniform distributed, with ramifications too extensive to guarantee plant stability

Basal suckers activity *(bact)*

The collar is a term that generally refers to the point on the axis of a tree where the root and shoot system meet (Del Tredici 2001). In mature trees, the collar develops just above the ground and is identifiable by the presence of numerous suppressed buds protruding from the trunk. When the bark is removed from the collar these buds are even more visible. Typically, there is a strong gradient of suppressed buds along the trunk of the tree with a maximum concentration in the collar (the concentration decreases the higher up the trunk one moves). The trunk of a tree at the base may also be enlarged by the storage of carbohydrates that serve as support for growth, but also for the proliferation of suppressed buds. The degree of collar activity of basal suckers with a diameter of less than 30 cm (*bact*) was obtained for the first inventory mainly from photographic material showing the lower part of the trunk. However, some useful indications were found in the text fields of the two-page sheets, where it is often written whether the collar was active or inactive. An example is the text describing tree ID22, where in the notes on the general health status it is explicitly stated that the collar is inactive.

The values of *bact* range from 0 to 2 in the usual increments of 0.5 (Tab. 5). In the second inventory, these values were obtained from field observations of the chestnut collar.

Table 5: Description of basal suckers activity scale values (*bact*).

Value	Description
0	No activity/proliferation
1	Moderate activity/proliferation
2	Important activity/proliferation

Degree of health condition (*all*)

In the first inventory and second inventory, the degree of health condition (*all*) of the monumental tree was estimated using an index between 0 and 4 (graduated with increment of 0.5). Where zero represents a completely dead tree and 4 a perfectly healthy and vital tree. The value is assigned after an overall view of the tree's condition, taking into account its vitality and chances for survival. The scale of this attribute is linear and the health assessment was made by scaling points from value 4 whenever characteristics that impair general health were seen.

Dead class and dead explanation (*dclass* and *dex*)

The dead class attribute (*dclass*) was used to classify the current status of the deceased monumental tree. Is it still standing? Has it collapsed on the ground? A number from 1 to 6 (Tab. 6) is used to describe the dead tree.

Table 6: Description of dead class scale values (*dclass*).

Value	Description
1	Tree still standing, almost all branches are dead but still attached to the structure
2	Tree still standing, only main branches still present
3	The tree has crashed to the ground and in some parts of its trunk the bark is still present.
4	The tree has crashed to the ground; trunk debarked and only a few structures are still recognizable.
5	Dead trunk still standing (usually the lower part)
6	Nothing remained

The ordinal attribute *dex*, on the other hand, is intended to describe the cause of death of the monumental tree which is classified as occurring due to natural or human causes or a combination of these both (Tab. 7).

Table 7: Description of dead explanation scale values (*dex*).

Value	Description
1	Environmental causes
2	Human causes
3	Environmental and human causes

Attribute *nails, marks, hut, ladd, stor, disc* and *dother*

Krebs systematically mentions the presence of nails (*nails1*), painted marks (*marks1*), huts and various constructions on the tree (*hut1* and *ladd1*), as well as the presence of extraneous material such as wooden planks in or around the chestnut tree cavity (Tab. 8). Often their presence was also documented through photographs. All information were transformed into ordinal attributes of boolean type, i.e. presence and absence.

Table 8: Description of attributes *nails*, *marks*, *hut*, *ladd*, *stor*, *disc* and *dother*.

Label	Description
nail	Presence of nails
marks	Presence of human made marks
hut	Hut/shelf on the crown
stor	Use of tree cavity as storage
ladd	Presence of ladder construction
disc	Discharge of materials around the tree
dother	Other damaging activity

In the second inventory the methodology consisted in the observation of these components during fieldwork. For each tree, the presence of a specific components was therefore systematically searched for**.**

Stability index

The stability index is intended to give a value to the overall stability of the monumental tree. The index takes particular account of the trunk and crown structure of the tree, leaving out the root system, which is usually not visible and difficult to assess.

All variables presented in the Table 9 were reduced to range between 0 and 1. In addition, if a variable was inversely related to stability, it was corrected by subtracting its value to 1. The table below shows all the variables initially considered for the construction of the stability index, as will be explained later, not all of them were eventually used.

Table 9: Table listing stability attributes considered for the construction of the stability index and their selected properties.

Label	Attribute name	Attribute type	Effect on stability
vcrow	Crown volume	Cardinal	Negative
slender	Slenderness coefficient	Cardinal	Negative
cc	Extent and severity of crown cracks	Ordinal	Negative
tc	Extent and severity of trunk cracks	Ordinal	Negative
vc	Compromised crown volume	Ordinal	Negative
cimb	Imbalance of the crown	Ordinal	Negative
cav	Degree of trunk cavity	Ordinal	Negative

Initially, 13 stability indexes were developed by summing and selecting the attributes shown in Table 9. The number of attributes used to determine the indexes ranged from a minimum of 3 to 8. A linear regression was then performed between the 13 indices and some inventory attributes with the intention of understanding and evaluating the newly created attribute. The index that showed the most statistically significant correlations (analyzing the p-value of the linear regression performed and the type of relationship, i.e. positive or negative) was the one constructed with all the attributes listed in Table 9, leaving out only the crown volume (*vcrow*). Linear regression was chosen for the general analysis and for this index, as no substantial differences were found when compared to more elaborate and complex regressions (e.g. quadratic...). It was chosen not to consider indices consisting of too many attributes and therefore to follow the principle of parsimony. The possibility of using the index directly in the field in the future was also considered, thus those attributes that could be easily (in terms of time and tools) obtained in the field were preferred.

The process of construction, analysis and screening led to the following index:

$$\boldsymbol{stability\ index\ = slender + cc2 + tc2 + cimb2}$$

The index proposed here describes the stability of the monumental tree only in the second inventory (only in this case the data are complete for all the attributes taken into consideration). The index may take a maximum value of 4 while the minimum value is set by the *slender* attribute, which may not equal 0.

Health index

The general health index is intended to complement and be a comparison to the attribute *all2* collected in the field. It was constructed in a similar way to the tree stability index and similar criteria characterised its construction.

Three attributes were taken into account for its development: the volume of the crown (*vcrow*), the health conditions of the bark (*barco*) and the extension of the bark (*barex*). The intention was again to include attributes describing the crown and trunk. The reader should note that the volume of the crown already contains other information about the crown, i.e. the missing volume of the crown, the compromised volume, the diameter of the crown and its thickness. In the case of this index, there were initially not so many attributes to be skimmed, since it was decided from the outset to exclude the attributes used for the stability index. The values of the indices were reduced so that they ranged from 0 to 1, thus dividing the value of each specimen by the maximum observed value**.**

A sum of the values of these modified attributes was used as follow:

$$\boldsymbol{Health - index = vcrow + barco2 + barex2}$$

The maximum possible value is therefore 3 and the minimum is 0.

4.4.2 Geographical and environmental data

The attributes that are part of the environmental and geographical data groups can be divided into four main themes. There are attributes relating to the forest area (*for20rX* and *for00rX*), attributes describing the site where the monumental chestnut tree is located (*rock, herb, slo, N*), those describing the geographic area such as latitude and longitude coordinates (other attributes are *alt, valley, mun, loc*) and finally attributes describing the built up area around the tree, in particular distance to paths and roads (*droad* and *dpath*) and built up area (*bu50* and *bu100*). Below, all these attributes are listed, described and the methodology used to record them explained.

Longitude and latitude (*lon* and *lat*)

Specification of the longitude and latitude of the location of the monumental chestnut tree. The reference system used is as follows: Swiss coordinate system based on the LV95 reference frame.

Altitude (*alt*)

Altitude of tree location expressed in meters above sea level. The reference system used is as follows: Swiss coordinate system based on the LV95 reference frame

Slope (*slo20* and *slo25*)

Average slope in degrees (sexagesimal) of the 25 x 25-meter (or 20 x 20 m) quadrant within which the monumental chestnut tree is located, calculated in a GIS environment on the basis of the national terrain model MNT25, which offers a grid of 1600 elevation values (40 x 40) for each square kilometer.

Northness (*N10* and *N40*)

The compass direction of a slope was transformed by means of the trigonometric cosine function into northness. This function provides values from -1 to 1 that describe the degree to which the slope (within a radius of 10m for *N10* and 40m for *N40*) on which the surveyed tree is located is north.

Valley (*valle*)

Descriptive attribute of the valley (see study area chapter) in which the monumental chestnut tree is located.

Municipality (*mun*)

Descriptive attribute of the municipality in which the monumental chestnut tree is located.

Location (*loc*)

Descriptive attribute of the location of the monumental chestnut tree.

Distance to a path and distance to a road (*dpath20* and *droad20*)

Distance of the monumental chestnut tree from any kind of path or road in the 2020 (respectively *dpath20* and *droad20*).

Built-up area around the tree (*bu50* and *bu100*)

Built-up area in cubic meter within 50 respectively 100 m of the trunk of the monumental chestnut tree.

Forest area (*forXr20, forYr50, forYr100*)

Forest area within a radius of 20 m (*forYr20*), 50 m (*forYr20*) and 100 m (*forYr100*). The "Y" in the label can take the indication 00 or 20 indicating the year in which the observation was made (2000 and 2020 respectively).

Herbaceous layer (*herb*)

Attribute describing the herbaceous layer in which the tree is located. The values of this attribute range from 0 to 3 and decimal values are not permitted (Tab. 10).

Table 10: Description of herbaceous layer scale values (*herb*).

Value	Description
0	No herbaceous layer (i.g forest soil mostly covered by litter)
1	Abandoned/wild meadow
2	Managed/cut meadow
3	Pasture/grazed meadow

Degree of rock cover (*rock)*

Attribute describing the degree of ground cover by rock (Tab. 11).

Table 11: Description of degree of rock cover scale values (*rock*).

Value	Description
0	Absent (no rocks or rock outcrops on the ground)
1	Modest (few rocks or rock outcrops on the ground)
2	Medium (ground with lots of rocks or rock outcrops)
3	Nearly complete (mostly stony ground)

4.4.3 Competition data

This category of data encompasses only four Attributes (Fig. 8), all of which are used to create the competition index. The attributes are given below, where the final part of the label names, the “X”, is in the individual data replaced by the cardinal sector in which the competing tree is located (e.g. aspN for a competitor in the northern sector). A description of the attributes belonging to this group is provided below.

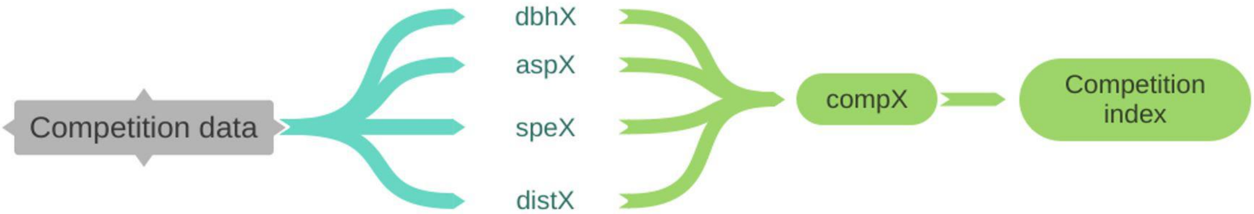

Figure 8: The diagram shows the four attributes of the competition data category and highlights their use in developing the competition index.

Cardinal sector (*aspX*)

Information on the competitor's cardinal direction in relation to the monumental chestnut tree was collected during the fieldwork with the auxiliary of a compass. The cardinal points were chosen by dividing the cardinal circle into eight sections resulting in the following sectors: N (North), NE (North-East), E (East), SE (South-East), S (South), SW (South-West), W (West), NW (North-West).

Competitors species (*specX*)

The attribute *specX* represents the species of the tree/shrub closest to the monumental chestnut tree under analysis within a radius of 15 m from its trunk in the *X* cardinal sector. The species name is given following the latin binomial nomenclature introduced by Linnaeus. The first letter (in capitals) identifies the genus, while the second identifies the species (written in lower case). If two plant species have the same wording, as many letters as necessary are added to the species part to distinguish them. If the species is not recognized, it is indicated by 'XX'.

Example: *Betula pendula* turns into "*Bp".*

Distance to competitor tree (*distX*)

distX represents the distance of the competitor tree/shrub species from the trunk of the surveyed tree (in the *X* cardinal directions). The measurement was carried out using a laser pointer (Leica Disto X3) and an arbitrary maximum distance of 15 metres was fixed.

Diameter class (*dbhX*)

dbhX embodies the class of trunk diameter at a height of about 130 cm above the ground of tree species (the diameter classes are shown in Tab. 13). The estimate was made by eye and in case of uncertainty a centimeter scale ruler was used.

Competition index

Several competition indexes exist in the literature, which apply different methods for its measurement. The first index to measure the competitiveness of a single individual was designed around 1950, when Gerrard defined an area of influence of trees based mainly on their size (Daniels et al. 1986). The degree of overlap of this area was thus supposed to give an indication of the degree of competition experienced by neighbouring competitor trees on the target tree. After this first attempt to measure competition, new attempts and new competition indices followed.

Despite the extensive literature, however, it was not possible in this research to find a suitable index to describe the situation of monumental chestnut trees. Indeed, competition indices are often used for the type of competition that occurs when the tree is still young or mature, and not centuries old. Monumental chestnut trees by definition have an extraordinary circumference and therefore also an extraordinary diameter; using conventional indices found in the literature, the comparison between trunk size (competitor species and monumental chestnut) is therefore biased. For this reason, after a comprehensive search for methods in the classical literature, it was decided to construct an ad-hoc index with the aim of best describing the competition situation for a monumental tree, which nonetheless suffers significant competition even despite its size, especially in places not managed by humans (Krebs et al. 2021).

For the realisation of the index, the footsteps of Hegyi (1974) were followed, he introduced a distance-dependent index that adds up the number of all competitors within a fixed predefined radius and takes on board in a mathematical formula the diameter of the trees (tree under analysis and competitors) and the distance between them (Daniels et al. 1986; Hegyi 1974). A fixed maximum radius was also maintained in this study, but not all competitors within this area were included for reasons of both number and resources. Besides, however, the species of the competitor tree and its position in relation to the eight cardinal directions were also included. A hazel bush has a different influence on the monumental tree than a beech tree, even if they are located at the same distance from the tree. A competitor tree located to the north of the monument tree also has a different influence than the same tree located to the south. In order to include these aspects, a classification and ranking (weighting factor) of the species and the cardinal position of the competitor tree was carried out. The competition index constructed here is thus intended to measure the degree to which the resources available to the monumental tree are limited by the number, size, proximity, position and species of competitors**.**

In this research there can be a maximum of eight competitors of the monumental chestnut tree under investigation (data relation 1:*n*, where *n* can take the maximum value of 8); in fact, each sector defined by the eight cardinal points only considers the closest competing tree to the monumental chestnut tree.

The distance between the competitor tree and the monumental chestnut tree (*distX*) was converted into a weighting factor (*distCor*) used for the competition index and designed to better describe the relationship between competition and distance (Fig. 9). It was therefore decided to assign a very high *distCor* value when the distance is minimal (maximum competition arbitrarily set as a value equivalent to 1). As the distance between the two trees (competitor and monumental chestnut surveyed) increases, the competition and therefore the *distCor* value decreases, although non-linearly.

$$\boldsymbol{distCor = 0.0016 * distX^2 + (0.0044 * distX) + 1.0014}$$

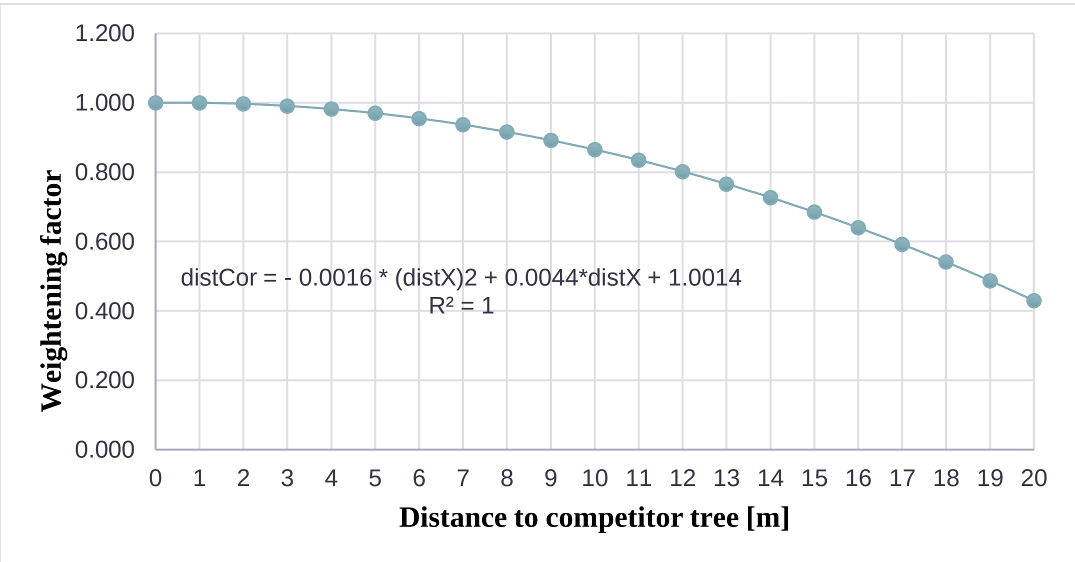

Figure 9: Graph showing the relationship between the distance to competitor tree (*distX*) on the x-axis and weighting factor (*distCor*) on the y-axis. The maximum distance taken into account in the index is 15 m, however, for graphical reasons the values on the x-axis go up to 20 meters.

In the field, each competitor was assigned a diameter class. It is assumed that on average maximum competitiveness is already reached when the tree reaches between 51 and 100 cm in trunk diameter at a height of 130 cm above the ground. At this diameter most species are already well developed and have reached or nearly reached their maximum growth rate. In concrete terms, the adjusted value (weighting factor) assigned to the diameter classes represents the ratio between the averages of the diameters of the various classes (Tab. 12).

Table 12: Table showing the adjusted value and e class number for each diameter class.

***dbh* [cm]**	**Class number**	**Adjusted value**
<12	1	0.02
12-30	2	0.2
31-40	3	0.5
41-50	4	0.8
51-100	5	1
>100	6	1

In this work, an attempt was made to assign a degree of influence of competitiveness to each cardinal direction. Each direction is thus assigned a value between one and zero whereby the higher value indicates a greater competitive influence on the monumental tree and vice versa for the lower value (weighting factor). The Table 13 shows the assigned value to each cardinal direction. The values assigned to each exposure were discussed and assigned through a consultation with expert Patrik Krebs.

Table 13: Table showing the assigned value and the label for each cardinal direction

Cardinal direction	**Label**	**Assigned value**
North	*aspN*	0.3
Northeast	*aspNE*	0.4
East	*aspE*	0.6
Southeast	*aspSE*	0.85
South	*aspS*	1
Southwest	*aspSW*	0.85
West	*aspW*	0.6
Northwest	*aspNW*	0.4

For each competitor of the monumental chestnut tree, the adjusted distance and diameter are multiplied with each other and with the values of the species and cardinal direction. The result of each competitor (*compX*) is then added up to obtain the total competition. The following calculation formula is therefore obtained:

$$\boldsymbol{Competition\ index} = \sum(\boldsymbol{distN} * \boldsymbol{diaN} * \boldsymbol{speN} * \boldsymbol{aspN}) + (\boldsymbol{distNE} * \boldsymbol{diaNE} + \cdots$$

4.4.4 Management data

The attributes that are part of the management data category can be divided into 3 categories: attributes concerning crown pruning, attributes concerning site management, and attributes concerning tree collar pruning (Fig. 10).

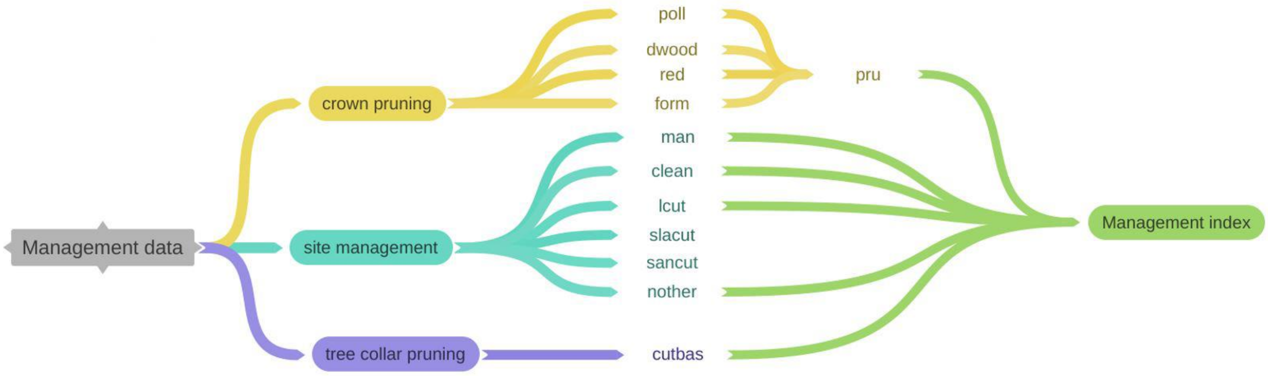

Figure 10: Diagram representing the various attributes that are part of the management data category divided into 3 categories: crown pruning (yellow), site management (sea green) and tree collar pruning (violet). The image also shows which attributes were used in the development of the Management index (light green).

Tree collar pruning

Cut of basal suckers *(cutbas2)*

This attribute describes the intensity of active and mechanical removal of basal suckers of monumental chestnut trees. The values of this attribute range from 0, i.e. no removal intervention and 3 radical removal intervention, i.e. all basal suckers have been mechanically removed (Tab. 14). The scale of this value assumes only integer values.

Table 14: Description cut of basal suckers scale values (*cutbas*).

Value	Description
0	No intervention
1	Punctual intervention
2	Moderate intervention
3	Radical intervention

Crown pruning

Attributes *dwood2 red2, poll2* and *form2*

These are designed to indicate the recognition of certain pruning interventions on the crown (Tab. 15). Their identification was often supported by oral sources which reported the type of crown pruning intervention and the time period in which it took place. If a pruning was present and if the purpose of the pruning could not be identified, the value of the attribute was not given (NA value). All these attributes are of the boolean type and therefore allow values of 0 (absent) or 1 (present).

Table 15: Descriptive table of attributes *dwood2, clift2, red2, poll2 and form2*

Label	Description
dwood2	Pruning with the aim of removing dead or dying portions of the crown.
red2	Pruning monumental chestnut trees to reduce height or width. Pruning of the chestnut tree crown with the aim of reducing its size. In particular the height or width.
poll2	Pollarding intervention on the crown of the monumental chestnut tree.
form2	Pruning of the crown of monumental chestnut trees with the aim of improving the shape of the crown.

Pruning intensity (*pru2*)

This attribute is intended to describe the intensity of pruning undergone by the crown of the monumental tree under examination. The values range from 0 to 3 and cannot take on decimal values (Tab. 16). A value of 0 indicates no intervention, while a punctual intervention, i.e. on a branch or a small part of the canopy, has a value of 1. A moderate intervention is indicated by a value of 2, which describes pruning in several parts of the canopy and therefore no longer punctual. The highest value on this scale refers to a drastic, radical and clearly visible intervention.

Table 16: Description of pruning intensity scale values (*pru2*).

Value	Description
0	No intervention
1	Punctual intervention
2	Moderate intervention
3	Radical intervention

Site management

Degree of selva management *(man)*

This attribute describes the degree of management of the chestnut forest (*man*) considering only mature or old chestnut trees planted, possibly grafted and cultivated mainly for fruit production. The values ranges from 0 to 2 (Tab. 17). This information for the first inventory was primarily derived from the photographs, but also from the text written in the documentation. In the case of the second inventory, instead, the values were the result of observations of the area surrounding the monumental chestnut tree.

Table 17: Description of degree of management scale values (*man*).

Value	Description
0	Abandoned selva
1	Minimal selva management
2	Managed or restored selva

Attribute: *lcut, salcut, clean, sancut, nother*

These attributes (Tab. 18) are ordinal with boolean type values. They are used to describe the recognition and presence of a certain characteristic (most silvicultural intervention) in the vicinity of the monumental tree.

Table 18: Descriptive table of attributes *lcut, salcut, clean, sancut, nother*

Label	Description
lcut	Presence of trees and/or shrubs cut with the aim of clearing the crown of the analysed monumental chestnut tree
salcut	Presence of tree and shrub cutting around the monumental tree position area with the purpose of recovering usable material (valuable timber) before it becomes worthless.
clean	Cleaning around the monumental chestnut tree in the sense of cutting grass, tidying up organic material on the ground, etc.
sancut	Presence of tree and shrub cutting to prevent spread of disease or insects in the surrounding of the monumental chestnut tree.
nother	Other type of neighbour management intervention

Management index

This index was created to group together all those attributes that can describe the degree of management on and around the monumental tree and subsequently preform an analysis on it and not separately on each individual attribute. It was therefore decided to include the attribute *pru2* which describes the degree of pruning of the crown of the chestnut trees analysed, the attributes *lcut2, clean2* and *nother2* which represent the interventions that took place in the area in which the specimen analysed grows (*salcut2* and *sancut2* were instead excluded as they were not found in any of the individuals analysed). The attribute *cutbas2* indicating the degree of pruning of suckers and basal shoots and the attribute *man2* describing the degree of management of the chestnut selva were also included. The sum of the values of these attributes should give an indication of the general degree of management. The formula used is summarised below:

$$\boldsymbol{Management\ index = pru2 + lcut2 + clean2 + nother2 + cutbas2 + man2}$$

The general management index does not include information contained in or derived from the first inventory and therefore focuses only on the 82 surveyed specimens still alive. The values of this index range from 0 to 10, with the value 0 being assigned to those monumental chestnut trees that have not undergone any type of intervention in the last 20 years on themselves or in the surrounding area. The attributes given most consideration and weight within the formula are *cutbas2, pru2, man2* which can have higher values (*cutbas2* and *pru2* maximum value of 3 while *man2* maximum value equivalent to 2) than the other attributes used.

4.5 Photographic material and methods

The photographs taken during the second intervention had three main purposes. The first was to document the current situation through images. The second purpose was to collect material for the subsequent construction of a 3D model of the lower trunk. While the third goal was to document the path of the metric rule on the tree trunk. This has changed in the course of the last twenty years and the photographs will be used in the future to ensure accurate measurement again when comparing circumferences over time.

The camera used was a *Canon EOS 90D* and the objective featured a 16-35 mm lens. The procedure adopted to obtain the second inventory photographs depends on the health status and circumference measurement of the monumental tree.

If the tree surveyed was dead, photographs were taken to document the position and condition of the dead tree. Approximately twenty photographs were taken from different viewpoints and distances from the tree trunk. Particular attention was also paid to the overall scene.

If the tree was still alive, but the circumference did not increase, a tripod was used to take a series of photographs around the circumference of the tree in order to document the passage of the metric ruler. In addition, a number of photographs were taken of the entire tree and in particular also of the crown. The number of photographs in this case was around 100 per tree.

If, on the other hand, the tree was found to be alive and its circumference had increased over the last 20 years, a series of photographs (200 to 300 shots) were taken of the lower part of the trunk with the aim of producing a 3D model. The process for obtaining images that can be used for the 3D model is explained in the following steps.:

Step 1: the tree trunk is marked at two points with colored pins (marked with two red circles in Fig. 11).

Step 2: three wooden pickets are hammered into the ground. A tripod equipped with a laser beam indicating an horizontal plane is placed within the area delimited by the three pickets. This plane (blue dotted lines in the Fig. 11) is then marked on the wooden pickets with rubber bands.

Step 3: the distance between a picket (usually the one furthest from the trunk) and the marked two points on the trunk is measured using a laser distance meter (*Leica Disto X3*).

Step 4: The lower trunk of the tree is photographed following an imaginary circumference about 1.5 m from the trunk.

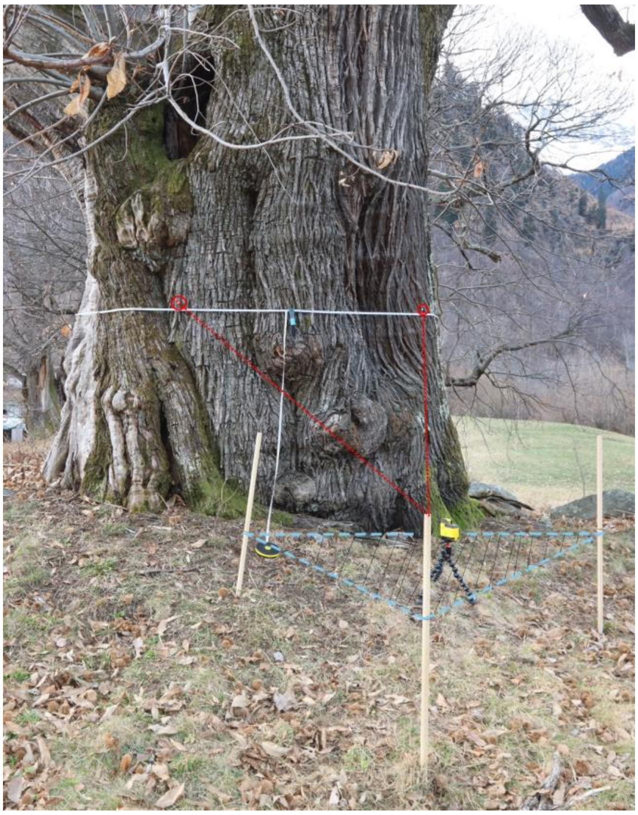

Figure 11: Photograph depicting a monumental chestnut tree, with graphics representing the workflow. Photograph depicting a monumental chestnut tree, with graphics representing the workflow. Red circles: colored pins, Dashed blue triangle: horizontal plane, Red lines: distance from the farthest stake to the two colored pins.

These two laser measurements (in step 3) can be used at a later stage to provide a reference measurement for the 3D model. The horizontal plane, on the other hand, can subsequently be reproduced in the 3D workspace and can be used to provide the correct inclination of the model. More than 200 photographs were taken for each specimen, which subsequently allowed the construction of a 3D model of seven individuals (ID26, 27, 51, 42, 44, 74 and 247). The use of a tripod was mandatory to guarantee the quality of the images. The aim of the 3D model was to document the complexity of the lower trunk of the tree and thus enable the visualization and possibly document the evolution of the structure in the future.

4.6 Data analysis

The analysis of the research data was mainly performed using the RStudio software (© *2009-2022 RStudio, PBC*). The basic software of R-studio was implemented and expanded through a number of R-packages (i.e. *rstan, dplyr, gplots,* …), which mainly enabled better graphic visualization.

RStudio was used to initially analyze the distribution of values of all attributes (in particular the data belonging to the tree data group), and then to develop graphs, specifically boxplots, in order to obtain and understand the possible relationships between the data. Afterwards, the most visibly significant relationships were chosen, and a linear regression was performed to better understand the significance of the relationships. A linear regression was chosen because by performing more complex and articulated regressions, the result changes extremely poorly.

Before the analysis, however, there was a data cleaning phase. Where all values entered and collated in an *excel* table were checked and verified. A subsequent check of the unusual data (outsiders) was carried out with the help of graphic visualization.

For the realisation of the 3D models, the *RealityCapture (RC)* photogrammetry software programme was chosen to be used.

5 Results

5.1 Current general condition of monumental chestnut trees in 2022

Q1: *"What is the current general health condition of monumental chestnut trees in the upper valleys of Canton Ticino?"*

The chapter 6.1 focuses on illustrating the current situation of the inventoried trees within the study area. The results in this chapter are based on the observation of 82 trees, i.e., the total number of living trees in the second inventory. The analysis is therefore built up only on a part of the data collected in the second inventory. It is worth mentioning and keeping in mind that tree ID236 has suffered a failure of the main trunk and therefore consists only of a basal sucker. As it is the only living remaining part of the tree, the basal sucker was then considered as a monumental tree in itself. In some analyses the observations of this monumental chestnut will be omitted. The omission will however be indicated each time.

5.1.1 Tree and competition data in the second inventory

According to the attribute *all2* about 50% of the inventoried surviving individuals have a health score of 1.5 or less, i.e. less than half of a perfectly healthy individual. No specimen reaches the maximum health grade (points 4 out of 4) and only 15 individuals (18%) exceed half of the scale of this attribute (Fig. 12).

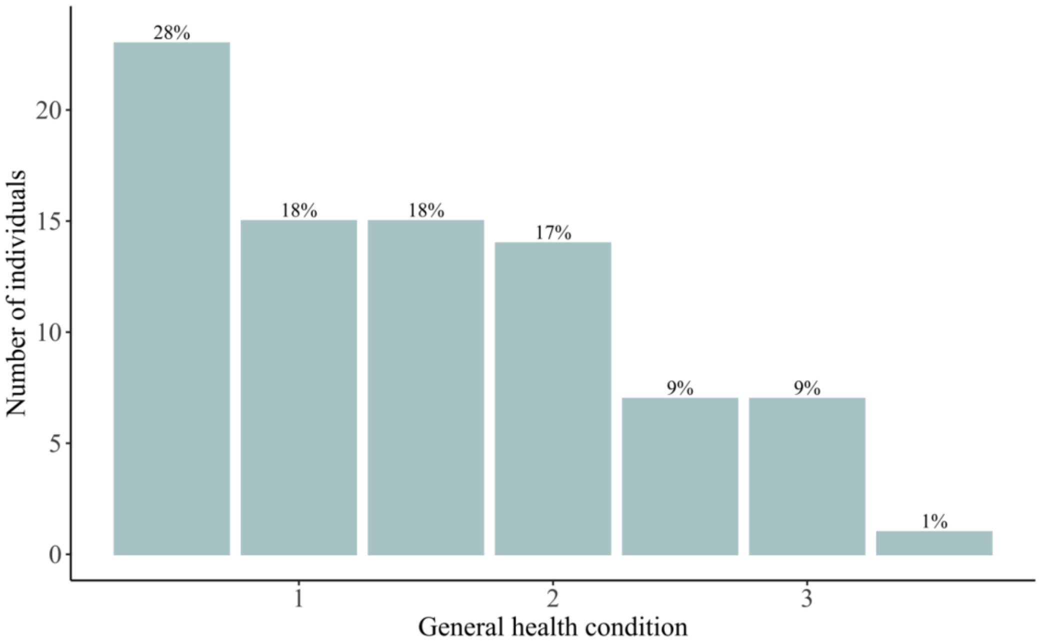

Figure 12: Distribution of inventoried trees according to classes of the attribute general health condition (*all2*). The x-axis shows the scale values of this attribute (linear scala with 0 = dead, 4 = perfectly healty and with 0.5 increment), while the y-axis counts the number of individuals per bar. Above each bar the percentage of observations over the total, i.e. 82, is also reported.

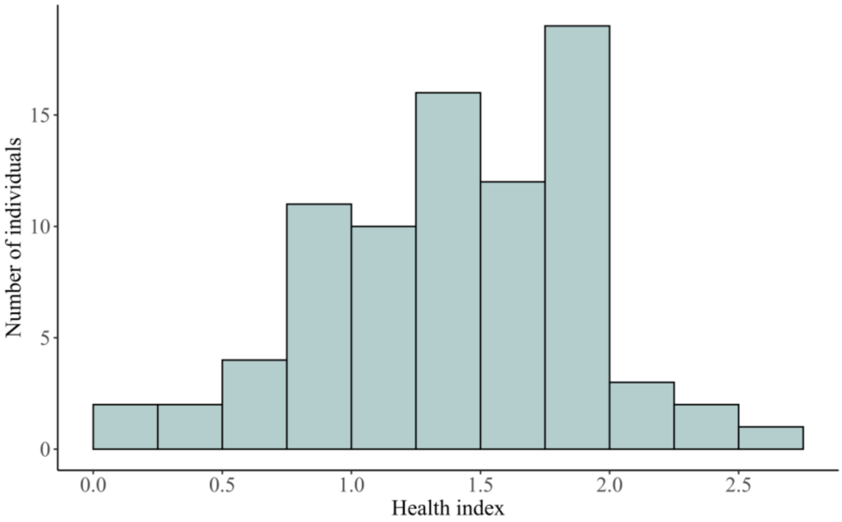

Figure 13: Distribution of individuals according to health index classes. The x-axis displays the values obtained for the health index, while the y-axis indicates the number of individuals observed per class.

The distribution of the data of the health index is almost "Gaussian"; the median and the mean lying more or less in the middle of the distribution, at a value of about 1.5 (Fig. 13). Most of the values are concentrated around the mean and only six individuals exceed a health value of 2, while 19 individuals have a health value less than or equal to 1. The distribution is therefore slightly shifted to the left with a peak coinciding with the median characterised by a sharp drop in the number of observations as the value of the index increases. The lower limit of the health index values is 0.014 while the upper limit is 2.71.

The most frequent crown geometric shape (*geo*) in this inventory was the conical figure representing almost 60% of the investigated crowns, followed by the sphere, the helipsoid and the cylinder. The average diameter (*da*) of the crowns is 10.5 m, while the maximum is 23.8 metres (Fig. 1 in Annex 4). There is one case in which the canopy has an average diameter of 0 metres. This is the chestnut tree ID78 which stands on a fluvio-glacial terrace in Guèr (Claro, Riviera valley). The trunk has almost completely collapsed, but a sucker of about 30 cm with a base inside the huge cavity of the tree climbs up the remaining dead trunk, giving rise to a still alive twig (see photographs in Annex 5), which nevertheless does not contribute in any way to the diameter of the crown and consequently to its volume. On average, the thickness of the crown (*cth2*) is 11.1 metres with a maximum of 30.6 metres (Fig. 2 in Annex 4). The attributes missing crown volume and compromised crown volume (*vm* and *vc* respectively), which are used to refine the geometric volume (*vg*) into the final volume of the crown (*vcrow*), both have a mean value of about 22% (Fig. 2 and 3 in Annex 4). The distribution of values is also similar, the peak of the distribution being between 10 and 20 %, higher rates at these percentages decreasing drastically. The average crown volume of monumental trees is 674 m^3 (Fig. 5 in Annex 4). Seven trees have a crown volume of more than 2'000 m^3 and the maximum volume is 5'130 m^3 for the tree ID62 (Fig. 14). This chestnut tree measures 28.5 m in height, of which 26.8 m is part of the crown. It has a very dense canopy especially in the upper section with a missing and compromised crown volume of 20% and 10% respectively.

Figure 14: Photographs showing the crown of individual ID62. The photo on the left shows the lower part of the tree and crown; on the right the upper part. Both photographs were taken in the year 2021 during fieldwork.

The most part of the analysed trees show crown cracks, but they are not very severe (Fig. 6 in Annex 4). Six trees have no visible crown cracks, while an equal number of trees have very severe crown cracks over almost the entire crown area. On average, the monumental chestnut trees have an irregularly distributed and therefore unbalanced crown (mean value *cimb2* = 2.2, Fig. 7 in Annex 4). Eight of the trees analysed have a very pronounced crown imbalance (highest value on the *cimb2* scale). Five individuals on the other hand have a very regular, well-distributed and apparently balanced crown. These are the individuals identified with ID78, 85, 97, 225 and 272. All of these trees share a relatively small crown size, they have either been severely pruned (pollard crown: ID85, 97, 225 and 272) or have suffered the collapse of part of the crown and trunk (Annex 5).

The maximum height reached by the investigated chestnut trees is 32.4 m and the mean value is 16.7 m (Fig. 8 in Annex 4). The mean circumference in the study area is 7.8 m, the minimum is 1.1 m while the maximum is reached with 11.8 m (Fig. 9 in Annex 4) by the chestnut tree ID43 located in the centre of the village of Chironico (Leventina Valley). On average, the trunk height of the inventoried trees is 3.96 m (Fig. 10 in Annex 4). Only two trees have a trunk height of more than 10 m (ID77 and ID49), while eleven trees have a trunk height of less than 2 m. Two monumental trees have a trunk height corresponding to the height of the tree, having undergone collapses and severe pruning, and having the crown constituted only by small shoots. On average, however, the trunk represents 23.75% of the total height of the chestnut tree.

Old trees with a large diameter tend to be usually compact (Mattheck 2007). In this study the mean diameter (*dbh*) of the analysed specimens is 2.47 m, while the mean value of the slenderness coefficient (*slender*) is 7.16, with a maximum of 36.56 and a minimum of 1.41 (Fig. 11 in Annex 4). Omitting the observation of ID236, which embodies a special case, the mean value of the slenderness would be 6.7, while the maximum value 13.5. No monumental chestnut therefore falls within the values considered dangerous for tree stability according to Mattechk (Mattheck 2007).

The median value of the degree of bark extension of the monumental trees under analysis is 2.5, i.e. the bark extends over more than half of the available trunk circumference (Fig. 12 in Annex 4). There is only one specimen with a bark extension less than 1 on the *barex2* value scale, i.e. the tree ID97 (Citt, Riviera valley). Six chestnut trees exhibit a complete bark extension. The median value for bark health condition instead is 3 (Fig. 13 in Annex 4). The bark of the surveyed trees is therefore quite healthy and characterised by few signs of weakness and dysfunction. A couple of individuals reach a practically perfect state of health of the bark, while five individuals are characterised by a *barco2* value less than or equal to 1.

The distribution of the degree of cavity (*cav2*) is distinctly shifted towards the right extreme (Fig. 15). Generally, the monumental trees have large cavities. About 50% of the specimens have a degree of cavity greater than or equal to 3.5 and 80% have a degree of cavity greater than or equal to 2 (i.e, an half of the maximum value). Only one specimen has apparently no cavities at all, namely specimen ID31 (Campi, Leventina valley). The presence of cracks on the trunk is a

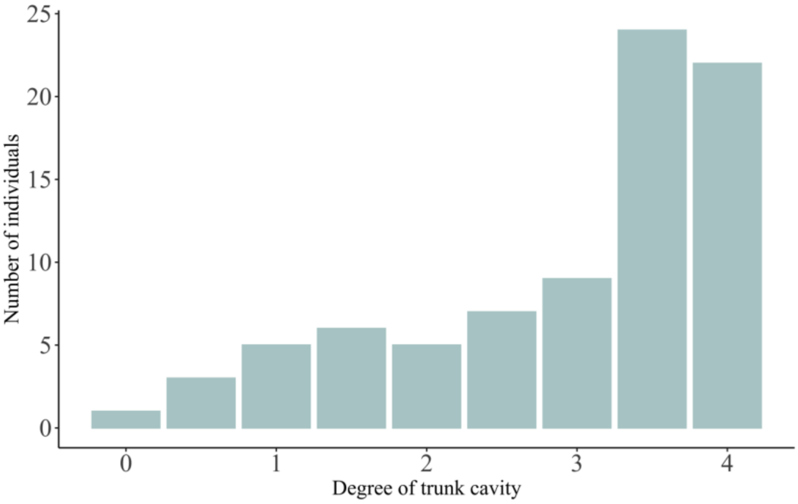

Figure 15: Distribution of individuals according to attribute class degree of trunk cavity (*cav2*). The x-axis shows the degree of cavity values (0 = apparently free of cavity, 1 = ¼ of the maximal cavity, 2 = ½ of the maximal cavity, 3 = ¾ of the maximal cavity, 4 = maximal cavity), while the y-axis indicates the number of observations per class.

characteristic feature of all the trees in this study. Only four individuals present a value less than or equal to 1 on the scale of the attribute *tc2*. The peak (and mean) of the distribution is found at a value of 3, with 21 observations. The maximum value of this attribute was instead observed on 13 specimens (Fig. 14 in Annex 4).

The collar activity (*bact2*) is on average between non-active and moderate (Fig. 15 in Annex 4). 31% of the chestnut trees under analysis had no collar activity and only 6% reached the maximum value.

The values of the stability index range from a value of 0.93 to 3.53, where higher values indicate a better overall structural stability of the tree. The mean score is around 2 (Fig. 16). Only six specimens exceeded the stability index value 3 (namely specimens with ID: 26, 49, 85, 93, 97 and 272). At the other extreme, ID85, 97, and ID272 which are characterized by a very reduced crown.

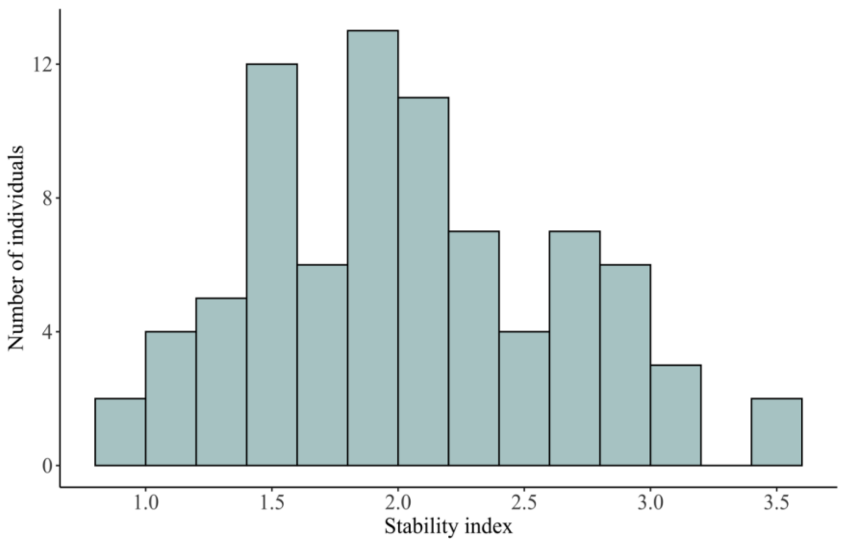

Figure 16: Distribution of inventoried individuals according to stability index classes. The y-axis shows the number of monumental chestnut trees with their respective while the y-axis shows the stability index values. Each rectangle of the histogram has a minor side corresponding to 0.3.

When studying a living organism such as a tree, it is important to investigate the relationships that may exist with other nearby living organisms. In this study an attempt was made to record information regarding possible competitor trees that surround the monumental tree. The information related to the competition suffered in the second inventory is firstly related to the attributes linked to the crown closure itself (*cclo2*) and the hierarchical position of its crown (*cpos2*) in respect to neighbouring crowns; and secondly the specific information of the closest competitors (competition index within a maximum radius of 15m, chapter 4.4.3).

The hierarchical position of the crown of the monumental chestnut is described by the ordinal attribute *cpos2*. 34% of the surveyed trees have a free-growing crown (*cpos2* value 0), whereas only 7% of the crowns are suppressed (*cpos2* value corresponding to 4, Fig. 16 in Annex 4). Twelve trees have a dominant crown, while 16 have a dominant to codominant crown (*cpos2*). About 20 trees have a crown that is in a codominant or intermediate position with respect to the crowns of neighbouring trees. About 20% of the surveyed trees have a crown free of competitors (*cclo2* = 0), and 13% of them have a completely closed crown (Fig. 17). The data show a low percentage of intermediate *cclo2* values (i.e., *cclo2* >1.5 and < 2.5). The monumental chestnut trees analysed therefore tend to have a fairly free or rather closed crown.

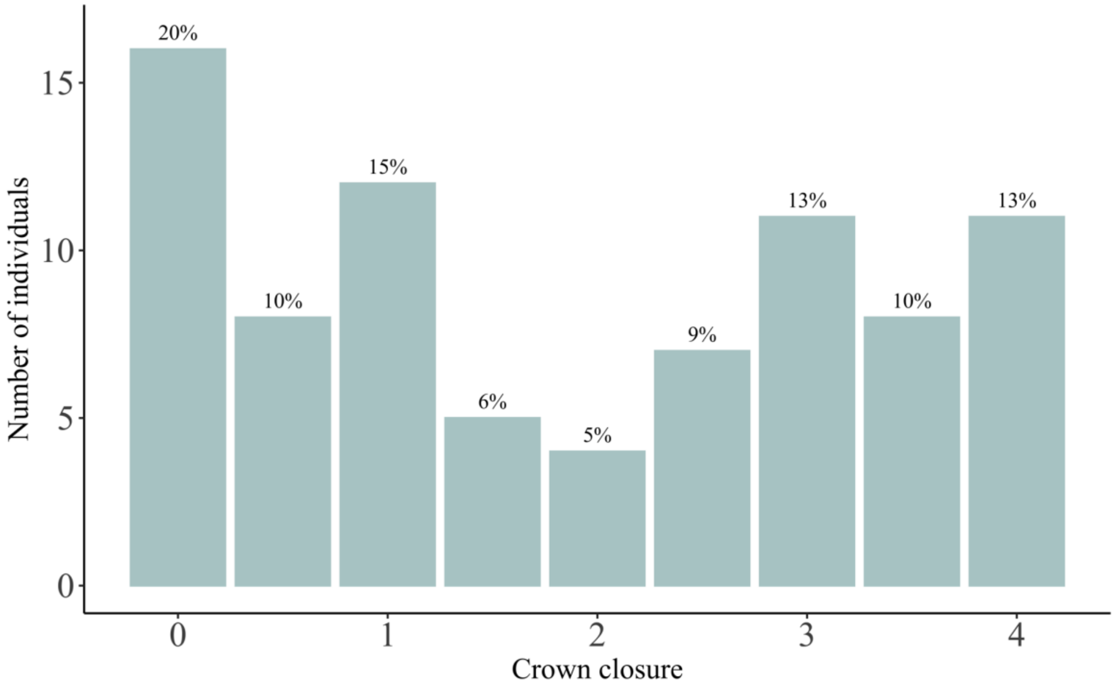

Figure 17: Number of individuals vs. crown closure (*cclo2*). The y-axis provides information on the number of individuals recorded while on the x-axis are the crown closure values (0 = free crown, 1 = ¼ Surrounded, 2 = ½ Surrounded, 3 = ¾ surrounded, 4 = closed crown). Above each column is the percentage of individuals belonging to that class.

The value of the index of competition suffered by the monumental chestnut ranges between 0 and 2.87, with an average of 0.9 (Fig. 18). Only five specimens (ID66, 70, 71, 128 and 280) have a score above 2.0 index value. The chestnut tree ID70 is the only tree with a very high value on the competition index scale, but with quite low values of crown closure (*cclo2* attribute scale value 2).

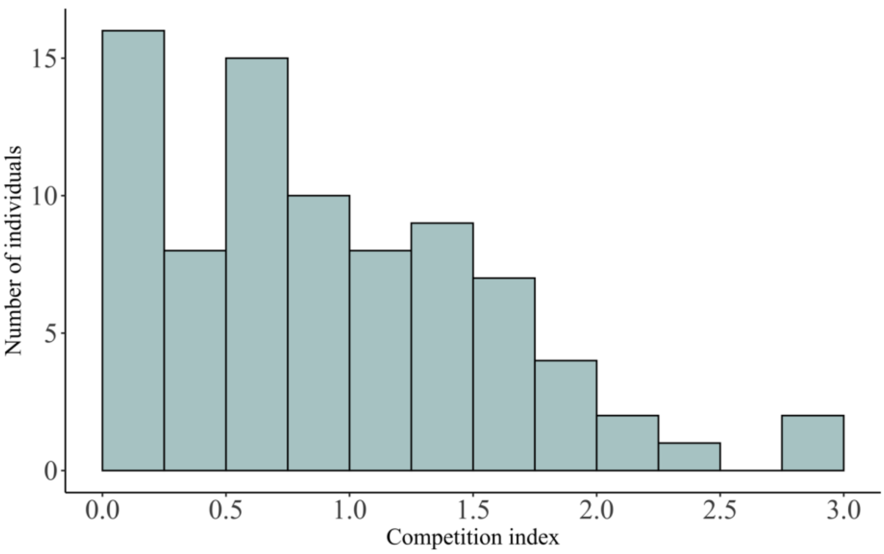

Figure 18: Distribution of inventoried individuals according to competition index values. On the y-axis is the number of inventoried chestnut trees while on the y-axis is the value of the competition Index.

The very high value found in the competition index is due in this case to the wide diameter of its competitors; in fact, four of the six competitors observed have a diameter (*dbhX*) greater than 80 cm.

The competitor species most present in the second inventory is *Castanea satvia* (*Cs*) with a total of 119 field observations followed by the species *Corylus avellana* (*Ca*) with 107 observations (Tab. 1 in Annex 6). With a large numerical gap, 45 specimens of *Betula pendula* (*Bp*) and 41 specimens of *Picea abies* (*Pa*) were also recorded (Fig. 19). The total number of competitors recorded in the second inventory is 397. with a mean of 5 competitors for each tree.

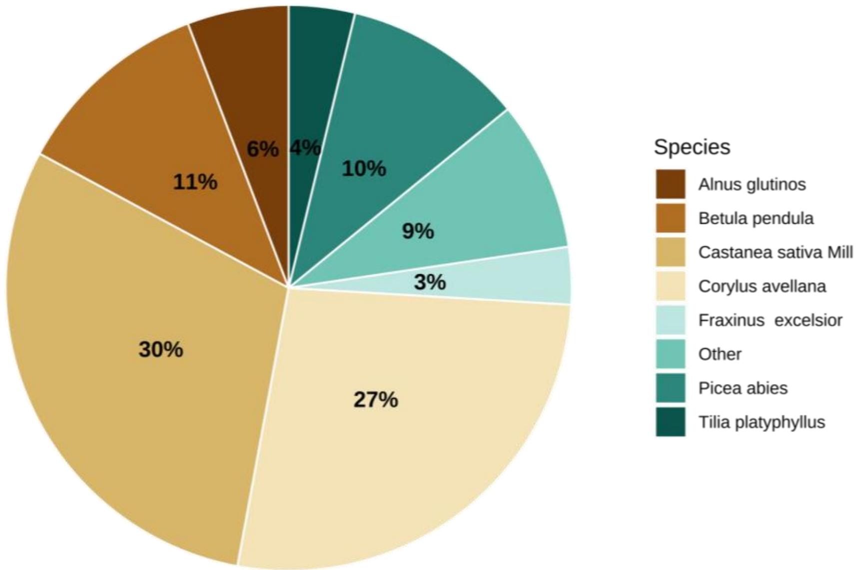

Figure 19: Percentages of competitor species observed during fieldwork. Under the category "other" are the following species: *Ailanthus altissima, Alnus incana, Acer pseudoplatanus, Fagus sylvatica, Junglas regia, Ilex aquifolium, Larix decidua, Prunus avium, Pinus sylvestris, Quercus petraea, Sorbus aucuparia, Tuja occidentalis*. In addition to these species under 'other' there are unidentified species (mainly ornamental plants) and the observation of a palm tree.

It can be noted that the sweet chestnut tree (*Cs*) and hazelnut tree (*Ca*) species make up more than half of the competitor individuals recorded. The sweet chestnut dominates in numerical terms the cardinal sectors: South, South-East, South-West, East and West, while in the North-West it shares its dominance with hazelnut (Tab.1 in Annex 6). The number of hazelnut competitors in the North-East and North is the highest compared to the other species. However, the northern sector also has many individuals belonging to the species *Picea abies*. The cardinal sector with the most competitors within a 15 m radius from the trunk of the monumental chestnut is the North-East sector (55 competitors), followed by the East (52), then the South-East (50), the North sector (46) and the South sector (45). The one with the fewest number of competitors is instead the South-West (44). It can be observed that the average competition on the monumental chestnut is higher in the cardinal sectors in the South (Fig. 20).

The average competition value in the South cardinal sector is in fact about 0.4, while in the North sector it is about 0.1, a quarter of the maximum average value. The competition in the South-East and

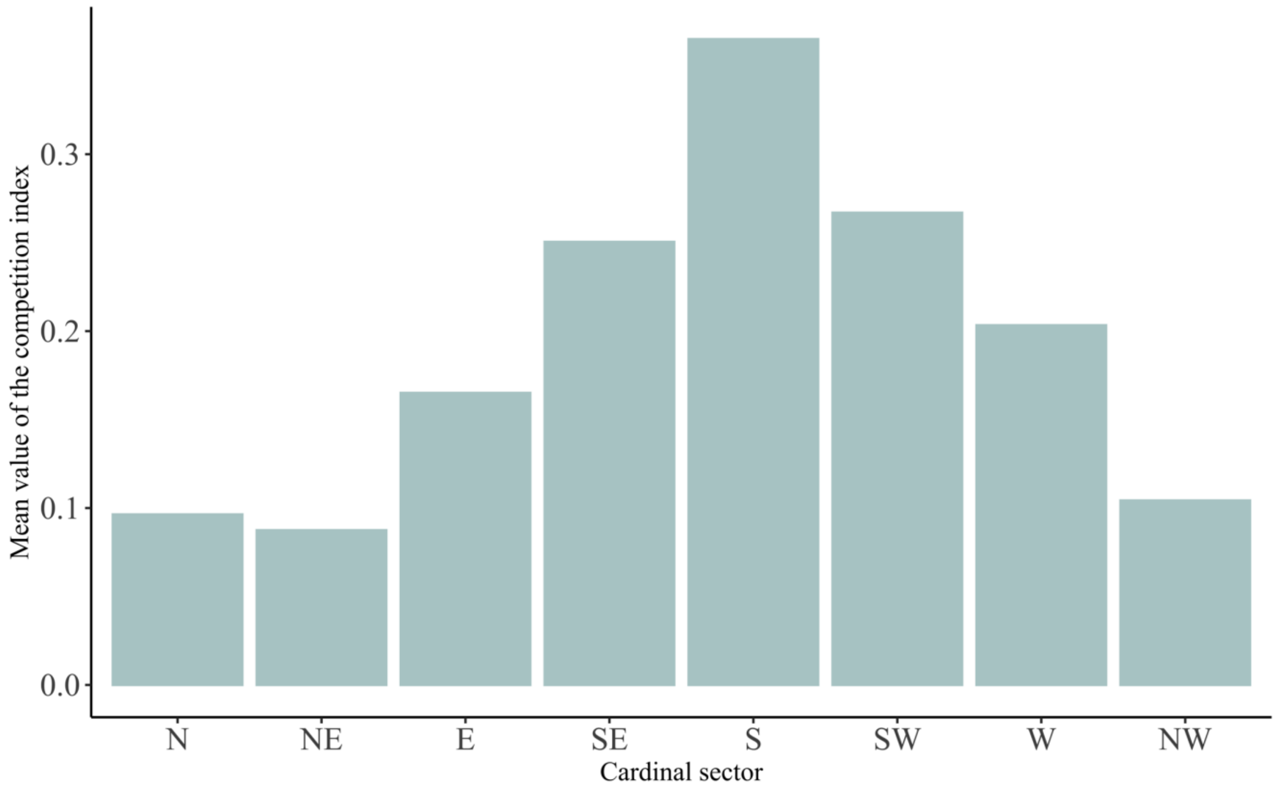

Figure 20: Average competition suffered by the monumental tree (y-axis) for each cardinal sector (x-axis).

South-West is on average about 30% lower than in the South cardinal sector. These results are also a consequence of the weighting factor factors used in Table 10, but since no distinction was made between East and West, it emerges from the results that competitors located in the West, on average, exert more competition on the monumental chestnut tree. The northern sector, which was assigned the lowest weighting factor, does not turn out to be the sector that exerts the least competition.

It was observed that the sectors closer to the south (including the south) are predominantly occupied by the species *Castanea sativa mill.*, the chestnut tree being in fact an important competitor on the species itself (intraspecific competition). The sectors with a less marked average of competitiveness are also the sectors with less presence of chestnut trees, they are in fact dominated by *Corylus avellana*, a species not too competitive against the monumental chestnut.

The mean distance of competitors from the monumental trunk in the eight cardinal sectors is between six and eight metres (Tab. 2 in Annex 6). The competitor species *Castanea sativa mill*. (*Cs*) is on average 8.2 m away from the monumental chestnut tree, while the species *Betula pendula* (*Bp*) is on average 8.1 m away. The average distance from the competitor species *Corylus avellana* (*Ca*) and *Picea abies* (*Pa*) to the monumental tree is instead respectively 5.7 m and 5.9 m (Tab. 3 in Annex 6). The chestnut tree as a competitor species was the species with the largest diameter, with 47 competitors exceeding 1 m in diameter at a height of 130 cm above the ground. *Corilus avelana*, on the other hand, was found to be the competitor species with the shortest mean diameter, However, this species was present in bush form, the stems were therefore multiple, and the space occupied by this species was actually larger than the diameter itself.

A high value in the attribute *all2* tends to correspond to a high value in the constructed health index (Fig. 21). Indeed, both attributes describing the general health of the analysed specimen correlated positively ($p < 0.001$). Nevertheless, it can be observed that *all2* values below 2, and especially equal to 0.5, have a great variability in the health index (Tab. 1 in Annex 7). There are therefore individuals whose health in the field has been assessed (attribute *all2*) as being just above the minimum (minimum corresponding to a zero value, i.e. a dead tree), but which achieve a higher and hence better health index score (Tab. 2 in Annex 7). The three specimens belonging to category 0.5 of *all2* with remarkably abnormal values for the health index are characterised by enormous trunk cavities (*cav2* = 4). This feature and others relating to the stability of the tree (e.g. *cc2*, and *tc2*) are in fact not taken into account for the construction of the health index (chapter 4.4.1), but appear to have had an influence in the field assignment of the *all2* value.

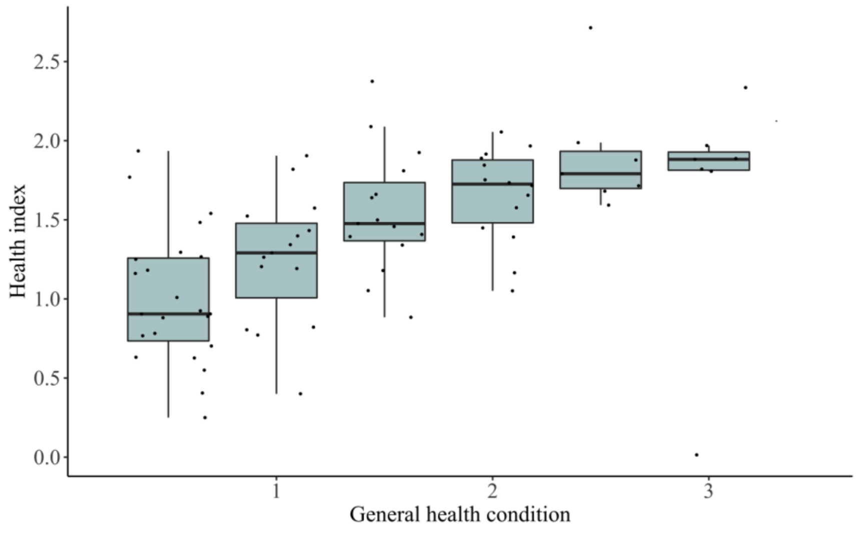

Figure 21: Relationship between health index and general health condition (*all2*). On the y-axis are the values of the health index while on the x-axis are the values of the general health condition (linear scala with 0 = dead, 4 = perfectly healty and with 0.5 increment).

Another individual with anomalous values with respect to the attribute *all2* and the health index is ID236, it has an *all2* value of 3 (high) and a very low score on the health index. This is mainly due to the very small volume of the crown compared to the other monumental trees being represented by a sucker. The two attributes *all2* and health-index indicate as monumental trees with greatest health two different specimens: ID26 and ID216 (Fig. 22). The values that differ greatly between them, are in particular those related to the canopy such as hierarchical position (*cpos2*), closure (*cclo2*), the volume of the crown (*vcrow*) and the competition index (Tab. 19). In fact the chestnut ID26 is located in a forest surrounded by many other trees and ID216, on the other hand, stands alone on a clearing and has no competitors in the surroundings.

Figure 22: Photos of individual ID26 (on the left) and individual ID216 on the right. Both photographs were taken in 2021 during fieldwork.

Table 19: Values of some attributes (named in the first line) of individuals ID216 and ID26.

ID	*compTot*	*cpos2*	*cclo2*	*vcrow*	*cc2*	*tc2*	*htree2*	*da*	*barex2*	*barco2*	*cav2*
216	0.791	3.5	4	3'662	3	2	20.1	18.8	4	4	4
26	0	0	0	1'277	0	0.5	21.7	17.2	4	3.5	3.5

The attribute *all2* positively correlates with the crown volume ($p < 0.001$) and with the components: thickness ($p < 0.001$) and average diameter ($p < 0.001$) of the crown. The general health (*all2*) also correlates positively with tree height (*htree2*, $p < 0.001$), bark extension and bark health condition (*barex2*, *barco2* both p < 0.001, Fig. 23). In contrast, it correlates negatively with the extent and severity of cracks on the trunk (p < 0.001), the degree of trunk cavity (p < 0.001, Fig. 24) and crown imbalance (*cimb2*, p < 0.05).

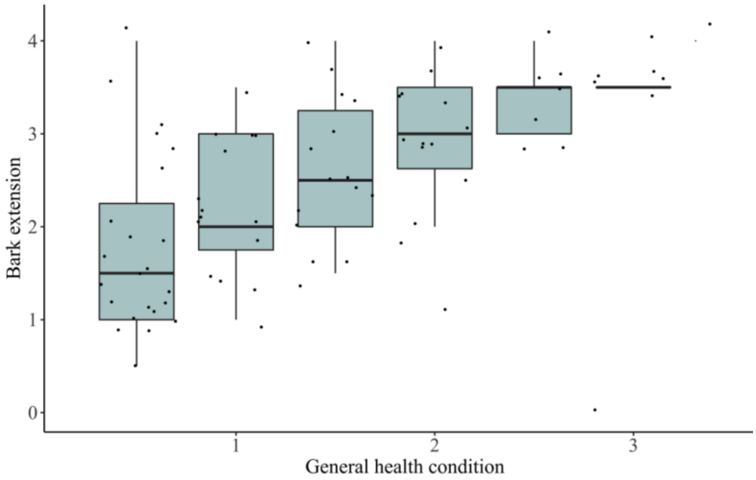

Figure 23: Relationship between the bark extension (*barex2*) and general health condition (*all2*). On the y-axis are the values of bark extension while on the x-axis are the values of general health condition (linear scala with 0 = dead, 4 = perfectly healty and with 0.5 increment).

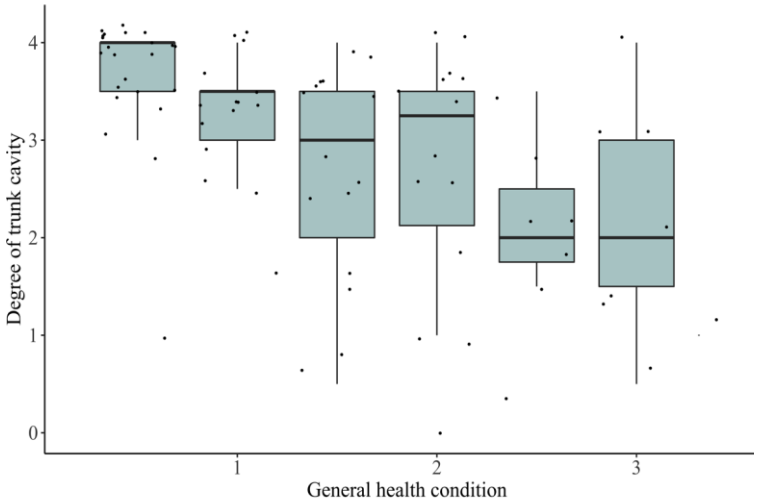

Figure 24: Relationship between the degree of trunk activity (*cav2*) and general health condition (*all2*). On the y-axis are the values of degree of trunk cavity while on the x-axis are the values of general health condition (linear scala with 0 = dead, 4 = perfectly healty and with 0.5 increment).

If linear regression between the different structural compartments of the monumental tree and the health-index is performed, significant relationships are obtained with the attributes used to construct the index (thus the bark extension, the health condition of the bark and the volume of the canopy). As for the attribute *all2*, there is a negative relationship with the degree of cavity of the trunk (p < 0.001). Unlike the attribute *all2*, the index constructed in this study shows a slight positive relationship (p < 0.1) with trunk circumference (*cir2*). Comparing *all2* and health-index shows that the first one is in a more significant relationship with the attribute describing the trunk cavity (p = 6.31×10^{-7} vs p = 6.02×10^{-4}).

The more extensive and healthier the bark on the trunk of the monumental chestnut tree (*barex2*, *barco2*), the greater the crown volume (p < 0.001 and p < 0.05 respectively, Fig. 26 and Fig. 1 in Annex 8). An extended trunk cavity (*cav2*) and the presence and severity of cracks on the trunk (*tc2*), on the other hand, correlates negatively with crown volume (p < 0.01 and p < 0.5 respectively, Fig. 2 in Annex 8). In general, it can be observed that the taller a tree is, the more the volume of the crown increases (Fig. 25), however, this last attribute is highly variable from a certain height (tree height around 20 m).

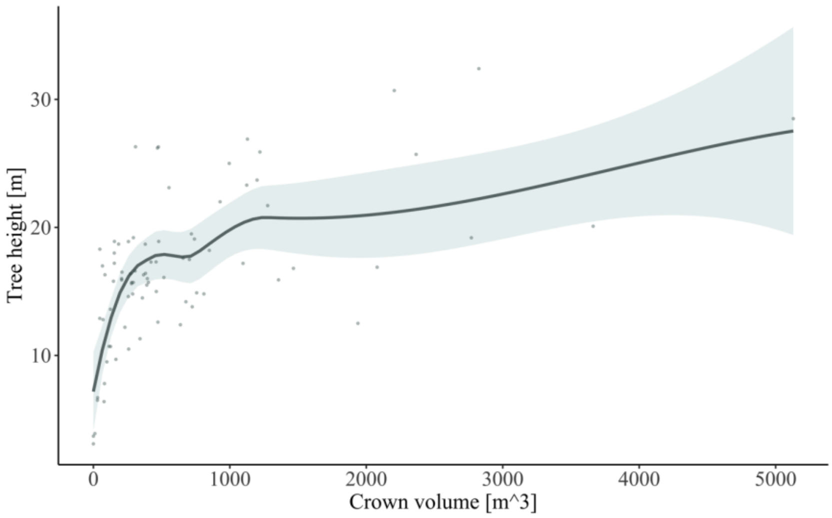

Figure 25: Relationship between the crown volume (*vcrow*) and the tree height (*htree*). The x-axis displays the volume of the crown expressed in cubic meters while the y-axis represents the height of the tree in meters.

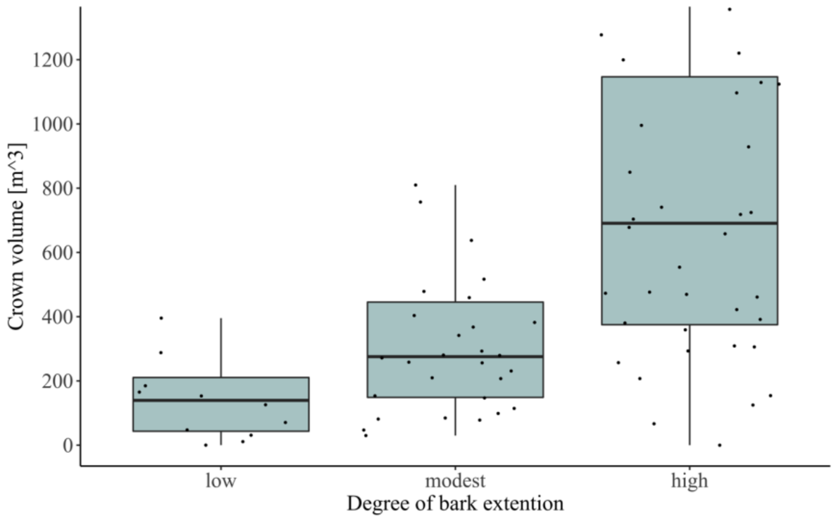

Figure 26: Positive relationship between degree of bark extension (*barex2*) and crown volume (*cv2*). On the x-axis we find the degree of bark extension divided into the following three groups: low (*barex2* <= 1), modest (1< *barex2* < 3) and high (*barex2* >= 3). On the y-axis, on the other hand, is the volume of the canopy in cubic meters.

The more compromised and cracked the crown (*vc* and *cc2*) of the sweet chestnut trees, the greater the crown imbalance (*cimb2*) and vice-versa (both relation: p < 0.001). *cimb2* also correlated positively with tree height (*htree2*, p < 0.001). Missing crown volume (*vm*), mean crown diameter (*da*) and degree of cavity extension (*cav2*) are also positively correlated with *cimb2* (both relation: $p < 0.001$).

Between the *barex2* and *barco2* attributes there is a very significant and positive linear relationship ($p < 0.001$); the higher the degree of bark extension, the greater its degree of bark health and vice-versa (Fig. 27).

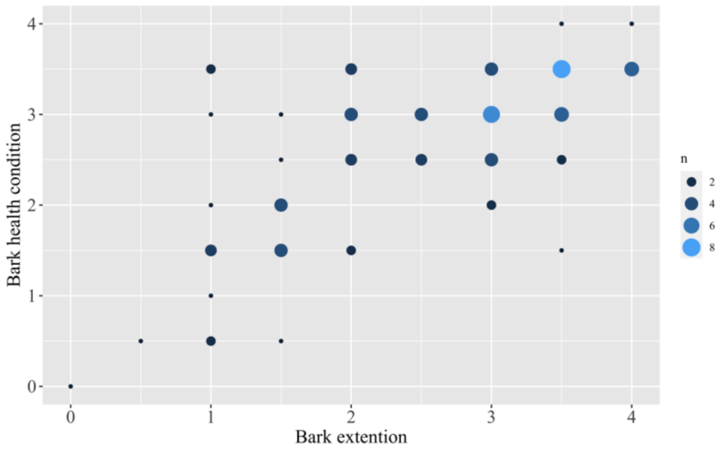

Figure 27: Positive relationship between the bark extension (*barex2*) on the x-axis and the bark health condition (*barco2*) on the y-axis). The colour and size of the dot indicate the number of observations (see legend on the right).

Analyses found that the more extensive and healthy the bark on a trunk (*barex2*, *barco2*), the greater the height of the tree and crown (both relationships: $p < 0.001$). Bark health also correlated positively with trunk circumference (*cir2*) and collar activity (both $p < 0.1$). The latter attribute is also positively correlated with tree height (*htree2*, $p < 0.1$) the mean diameter (*da*, $p < 0.05$) and the extent and severity of cracks in the crown (*cc2*, $p < 0.01$).

The extent and health condition of the bark on the trunk of monumental trees are negatively correlated with the degree and severity of cracks on the trunk (*tc2*, both relation: $p < 0.001$). The same degree of significance can be observed for the relationship between the attribute *tc2* and degree of cavity of the trunk (*cav2*), which is, however, positive. The relationship between the extent and severity of the cracks on the trunk (*tc2*) and the volume of the crown (*vcrow*) of the secular tree is also significant. In this case, linear regression analysis shows that the more the trunk is affected by cracks, the more restricted the volume of the crown is restricted ($p < 0.05$).

The stability index correlated positively ($p < 0.1$) with the attribute describing the general health condition of the tree (*all2*) but did not correlate significantly ($p = 0.222$) with the health index. It is instead significantly correlated with the compromised crown volume (*vc*, $p < 0.001$) i.e. the more a crown is compromised, the lower the overall stability of the monumental chestnut trees analysed (Fig. 28). A negative relationship was also found between the stability index and trunk cavity (*cav2*, $p < 0.001$), the average crown diameter and height (*da*, *cth2* both $p < 0.01$) and the collar activity (*bact2*, $p < 0.05$).

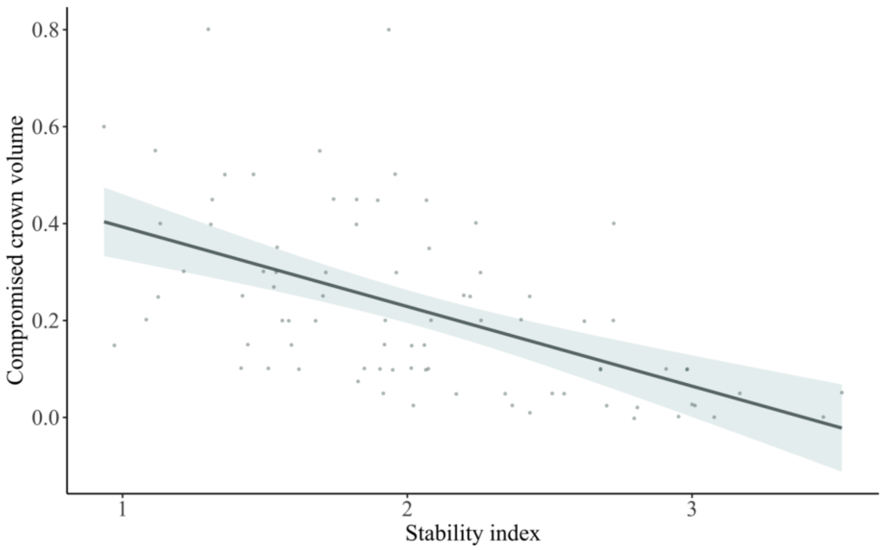

Figure 28: Relationship between the stability index and compromised crown volume (*vc*). On the x-axis are the stability index values while on the y-axis is the compromised portion of the crown volume.

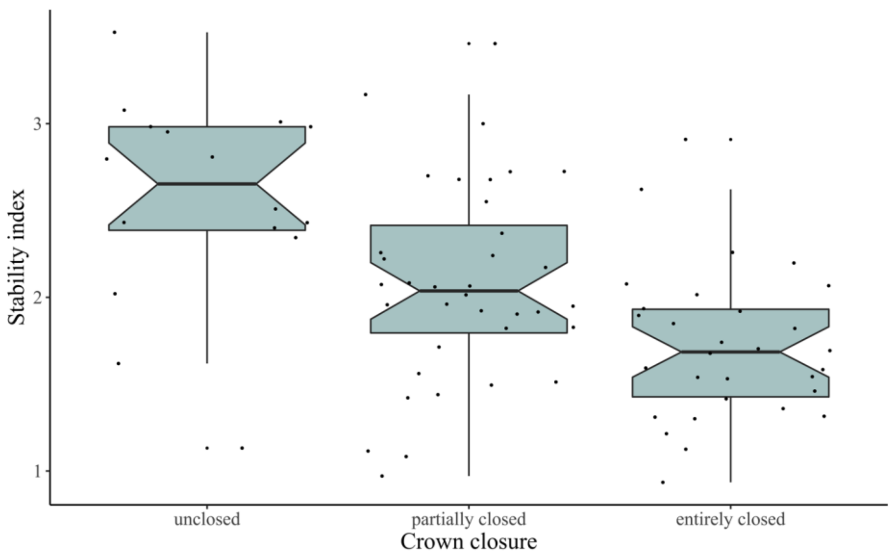

Figure 29: Stability index vs. crown closure (*cclo2*). On the x-axis are the crown closure values grouped the 3 categories: unclosed (*cclo2* value = 0), partially closed (0.5 <= *cclo2* value < 3) and entirely closed (3 <= *cclo2* value <= 4). On the y-axis are the stability index values.

Both the attribute *cclo2* and the attribute *cpos2* are positively correlated ($p < 0.001$) with compromised crown volume (*vc*), extent and severity of crown cracks (*cc*), as well as with crown imbalance (*cimb2*). The more the crown of the monumental tree is surrounded and dominated by other crowns, the more it appears to be weakened and unbalanced. It also emerges from the analysis that the stability index of the tree is lower when the values of *cclo2* (Fig. 29) and *cpos2* are high ($p < 0.001$ for both relation).

The competition index is also positively related to the crown closure (*cclo2*, p< 0.001), canopy hierarchy position (*cpos2*, p < 0.001) and crown imbalance (*cimb2*, p < 0.001) and also with the compromised crown (*vc*, p < 0.001) and the degree and severity of crown cracks extension (*cc2*, p < 0.01). When the crown of the chestnut tree is therefore closed, unbalanced and at a disadvantageous position to receive sunlight, competition is very high.

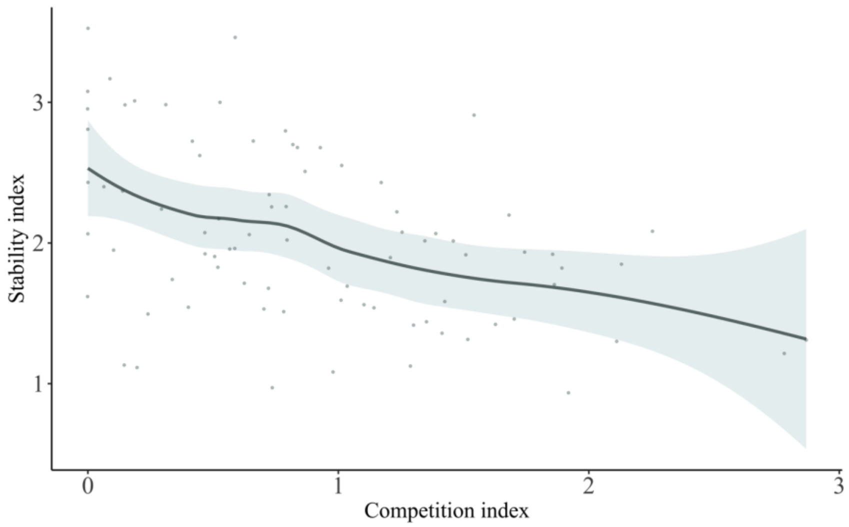

Figure 30: Stability index vs competition index. On the x-axis are the competition index values while on the y-axis are the stability index values.

The competition suffered by the chestnut tree has a negative relationship (significant with a p-value of less than 0.001) with the stability index of the monumental tree (Fig. 30). It can be seen, however, that specimens with a low degree of competition have a rather variable stability, while specimens subjected to a high degree of competition from neighbouring trees tend to have a smaller variable. The degree of bark extension (*barex2*), on the other hand, correlates negatively (p-value < 0.01) as does the general health (*all2*, p < 0.01, Fig. 31) with the competition index.

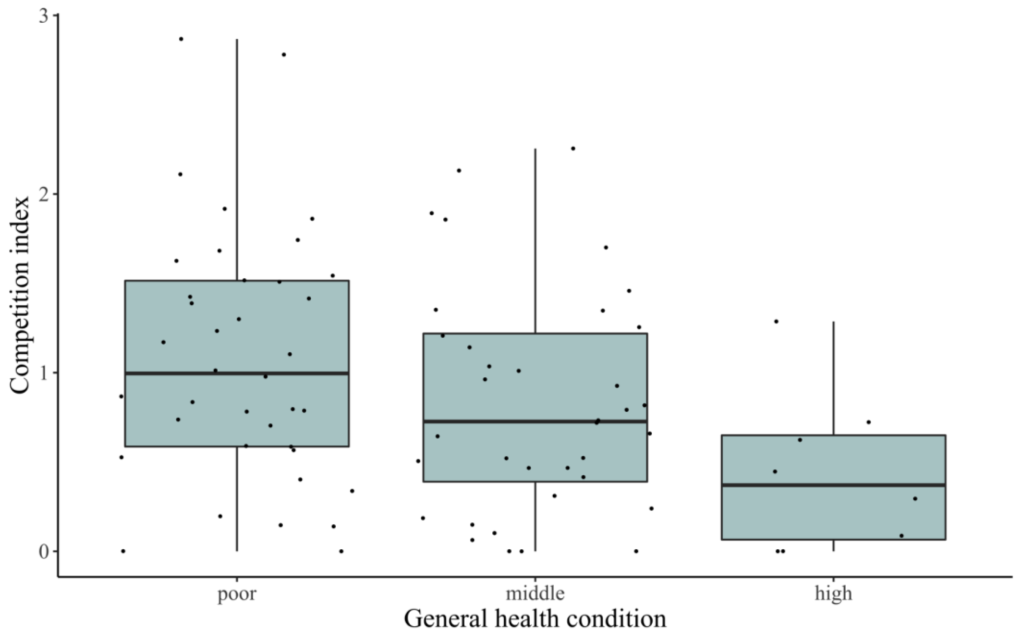

Figure 31: Competition index vs. General health condition (*all2*). On the x-axis are 3 classes of the attribute General health condition (*all2*): poor (*all2* value <= 1), middle (1< *all2* value <= 2.5, high (*all2* value > 2.5). On the y-axis, on the other hand, the Competition index values are found.

The health index on the other hand, although also negatively correlated, obtained a p-value lower ($p < 0.1$) than the value of the attribute *all2* established during the fieldwork. A list of significant relationships between the indices, the general health condition (*all2*) and the attributes of the tree data group can be found in Annex 9.

5.1.2 Geographical and environmental data in the second inventory

The distribution of the *all2* attribute by health class (first column, Tab. 20) in the three valleys under analysis is fairly similar for the two upper valleys, while for the Riviera valley the percentage of monumental trees with a health class between 0.5 and 1.0 is almost 10% higher; on the other hand, the percentage of trees in relation to the total with a health class between 1.5 and 2.0 is about 10% lower (Tab. 20).

Table 20: Number and percentage of observations divided by analyzed valleys and by health class (attribute *all2*).

all2	**Blenio**		**Leventina**		**Riviera**	
class	Number of trees	[%]	Number of trees	[%]	Number of trees	[%]
0.5 - 1.0	2	40	15	42	21	51
1.5 - 2.0	2	40	15	42	12	29
2.5 - 4.0	1	20	6	16	8	19

The trees in the Blenio valley, followed by those in the Leventina valley, have on average a greater circumference than those in the Riviera valley (Annex 10).

The analysis did not indicate significant correlations between the attribute *all2* and the geographical environmental attributes (Tab.1 in Annex 11). A negative relationship was found with the forest cover (*for20r100*, $p < 0.05$) and the slope within a radius of 25 m from the analysed specimen (*slo25*, $p < 0.1$).

The stability index, on the other hand, correlates with many environmental and geographical attributes (Tab. 2 in Annex 11). In general, a positive relationship emerges with the herbaceous layer of the soil, i.e. the more the herbaceous layer is managed by humans or is used as pasture land, the greater the stability of the tree seems to be (*herb2*, $p < 0.001$). The built-up area (*bu50* and *bu100*) is also positively correlated with the stability index ($p < 0.01$). While the forest cover of the area (*for20r20*, *for20r50, for20r100*) has a negative correlation with the index (all relation characterised by $p < 0.001$). The slope of the terrain (*slo20*) also appears to be negatively correlated, as does the degree of ground rock presence (*rock2,* $p < 0.05$). The analysis also revealed a slight positive correlation with the altitude (*alt,* $p < 0.1$) at which the tree is located; trees with greater stability also tended to be found at higher altitudes.

The competition index besides being positively correlated with the forest cover of the area (*for20r20, for20r50, for20r100*, $p < 0.001$) was also found to be negatively correlated with the built-up area (*bu50*, *bu100* $p < 0.01$, Tab. 3 in Annex 11). Northness (*E10, E40*) also appeared to be in a (negative) correlation with the competition index ($p < 0.01$) indicating greater competition if the surveyed specimen is located on a southern slope.

5.2 Evolution of the monumental chestnut trees (from 2000 to 2022)

The main purpose of chapter 5.2 is to investigate the answer to the second research question, namely:

Q2: What are the dynamics and changes that have characterised the last twenty years of the monumental chestnut trees?

A total of 19 individuals died between the first and second inventories (Annex 12). The Blenio valley has not recorded any deaths in the last 20 years, while in the Leventina valley and the Riviera valley died respectively 8 and 11 trees. The total percentage of deaths of chestnut trees analysed in this study is therefore 18.8%, the percentage of deaths in the Leventina valley is 18.2% and in the Riviera valley 21.15%.

5.2.1 Tree data over the last 20 years

The average of the attribute *all1* of all the chestnut trees analysed in this research is 1.75, while the average excluding the nineteen dead individuals is 1.84 (Fig. 32). It can therefore be observed that the average health of the dead monumental trees (1.37) is lower than the average health of the alive specimen.

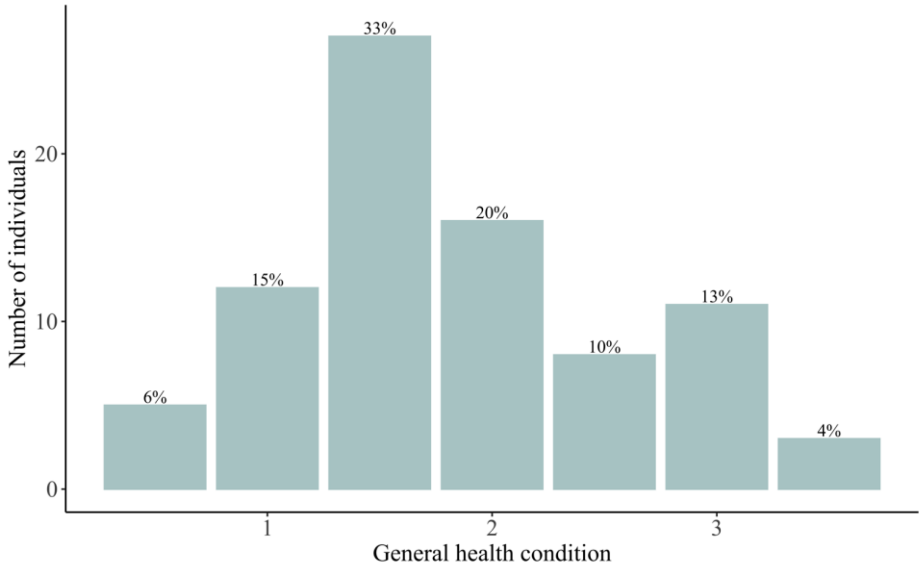

Figure 32: Distribution of inventoried trees according to classes of general health condition (*all1*). On the x-axis are the values of the general health condition (linear scala with 0 = dead, 4 = perfectly healty and with 0.5 increment) and on the y-axis are the number of individuals. At the top of each column is presented the percentage of inventoried trees belonging to that general health condition class.

The cause of tree death is complex, often multiple factors are at play that are difficult to identify. Within the framework of this research, an attempt was made to classify death as due to environmental factors (wind, forest fires, etc.), human factors (felling, mechanical removal, etc.), or a combination of both (the attribute that assigns the defined cause to each individual death is *dex*, more information about this can be found in chapter 4.4.1). The analyses show that the main cause of death of the monumental chestnut trees investigated is due to environmental factors (11 individuals out of 19). Annex 13 contains comparative photographs of the dead specimens during the first and second inventories and a description containing hypotheses on the circumstances of their death. It can be deduced from these descriptions and from the photographs taken during the fieldwork that almost all the dead trees have crashed to the ground and still have their main trunk more or less intact (attribute *dclass*). Only two dead specimens are still standing, namely the individuals ID89 and ID55. The cause of death of ID89 was not at all clear during the fieldwork; the tree in fact still has all structures (trunk and branches) intact but is completely dry. In the first inventory the notes refer to a disease, this could be a plausible explanation for its death. Some of the trunks of the individuals found crashed on the ground still had parts of bark more or less intact, it is assumed that these individuals died suddenly due to a structural failure, perhaps due to wind, or to overloading of the canopy due to snow. Other trunks on the ground were barkless, for these individuals it is presumed that the death was not very recent, or that there was a disease or drying up of the vital structures before the crash. Three of the 19 dead chestnut trees (ID40, ID95 and ID248) were labelled as having died by human hands, all of which had clean cuts probably due to the use of a handsaw or more likely a motor saw. Without oral sources it is however difficult to know whether the tree was already dead at the time of human intervention (see photographs in the Annex 13). For the trees ID40 and ID95 no oral sources were available to confirm the hypothesis, but for individual ID248 an interview with the man who removed the monumental chestnut tree was carried out and the cause of death by human hands was therefore confirmed. The monumental chestnut trees ID40 and ID95 were located adjacent to residential buildings (ID40) and/or busy roads (ID40 and ID95). Their deaths were therefore presumably caused by human intervention to protect these properties. Four of the 19 dead trees were classified as having died due to either natural causes or human intervention (ID55, ID88, ID100 and ID269). In the case of monumental chestnut trees ID55 and ID100 oral sources consulted during the fieldwork reported that after an episode of strong wind the tree was dying and unsafe. In the case of the chestnut tree ID55, the canopy was reduced to prevent the imminent collapse of the tree, which died not long afterwards (Annex 13). In the case of the chestnut tree ID100, the source reveals that a decision was taken immediately to remove it, since goats were grazing in the meadows where the tree was located.

From the analysis of *all1* of the dead trees emerged that there is no significant pattern between the level of health they had 20 years ago and the cause of death. There are in fact chestnut trees with good health (*all1* = 2) that have died of both natural and human causes (Annex 12). Most of the chestnut trees removed by humans, however, had a health of less than 1.5 (four individuals out of seven).

When comparing the structural compartments of chestnut trees that have died in the last 20 years and those that are still alive, three interesting main differences emerge.

It was found that the basal suckers activity (*bact1*) of chestnut trees that died during the first inventory was on average lower (average *bact1* = 0.34) than in those that survived (0.76, $p < 0.01$). On the scale of this attribute, it can therefore be seen that basal suckers activity in the 2000s was almost absent in chestnut trees that subsequently died, while it was modest for those now still alive (Annex 14).

On average the crown of the deceased trees was more unbalanced during the first inventory mean *cimb1* = 2.65, while for the still alive trees the value was around 1.9 ($p < 0.05$, Fig. 33). The hierarchical position of the crown in comparison to the adjacent crowns also shows a substantial difference between dead and living trees. On average, the dead specimens had a co-dominant and intermediate crown in the first inventory mean *cpos1* = 2.23, while the living specimens had a crown hierarchical position free of other crowns or dominant mean *cpos1* = 1.9 over the surrounding ones ($p < 0.01$, Fig. 34).

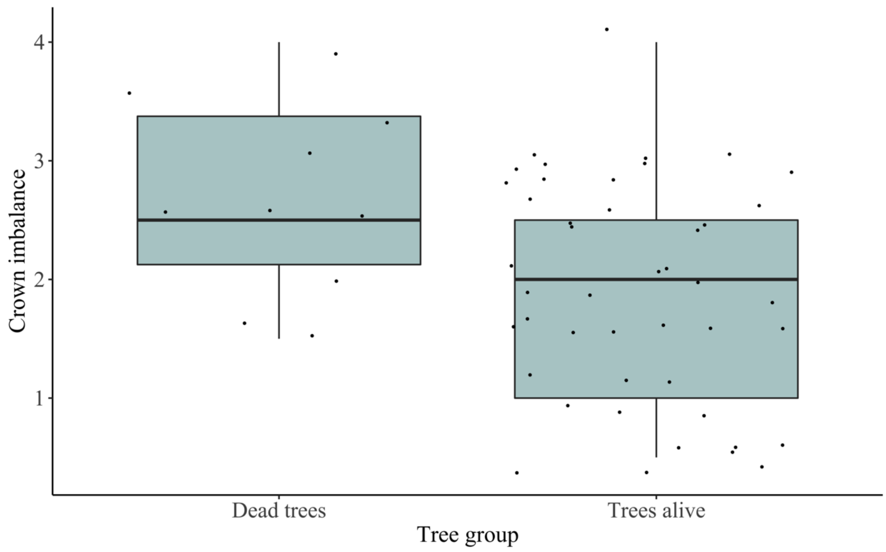

Figure 33: Crown imbalance (*cimb1*) vs. tree group. On the x-axis we find the two tree groups (dead and alive) while on the y-axis we find the crown imbalance values (0 = stable, well-distributed and balanced crown, 1 = between stable and slightly unstable crown, it is unevenly distributed in space, 2 = slightly unstable and unevenly distributed crown, 3 = clear structural imbalance of the crown that could compromise the structure stability of the tree, 4 = strong structural imbalance in the crown. Branches not uniform distributed, with ramifications too extensive to guarantee plant stability)

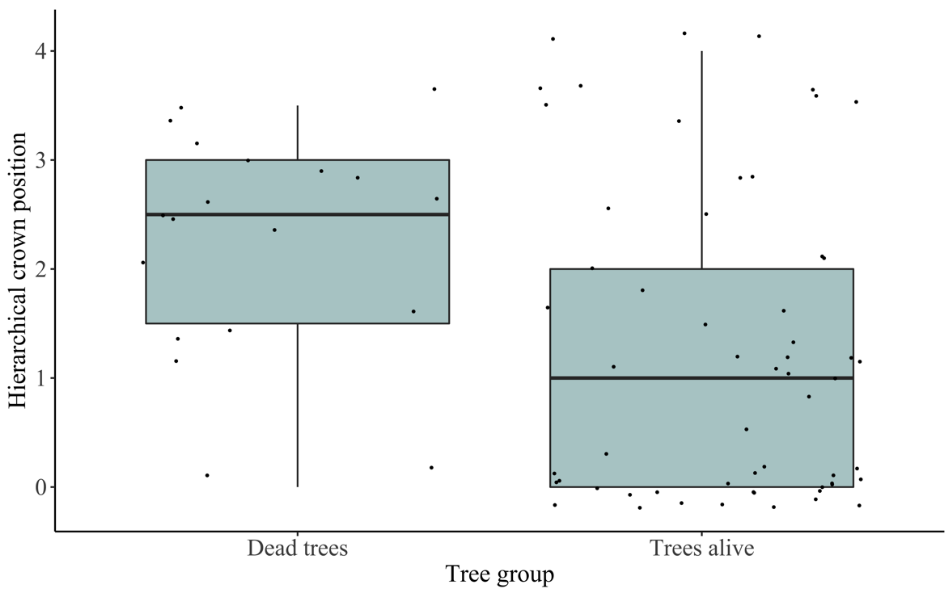

Figure 34: Hierarchical crown position (*cpos1*) vs. tree group. On the x-axis we find the two tree groups (dead and alive) while on the y-axis we find the hierarchical crown position values (0 = open grow, 1 = dominant crown, 2 = co-dominant crown, 3 = intermediate crown, 4 = suppressed crown).

In order to understand how the situation for monumental chestnut trees has evolved over the last twenty years, the evolution of the attribute related to the general health condition (*all1* and *all2*) is presented below (Fig. 35). If the value on the x-axis is negative it means that the general health of the monumental chestnut tree has decreased, a positive value indicates an increase in the general health condition. Just having values in the positive part of the x-axis is surprising and indicates that the general health of a centuries-old specimen of *Castanea sativa Mill.* can improve over time. However, it is necessary to go into detail to understand the extent and causes of this improvement.

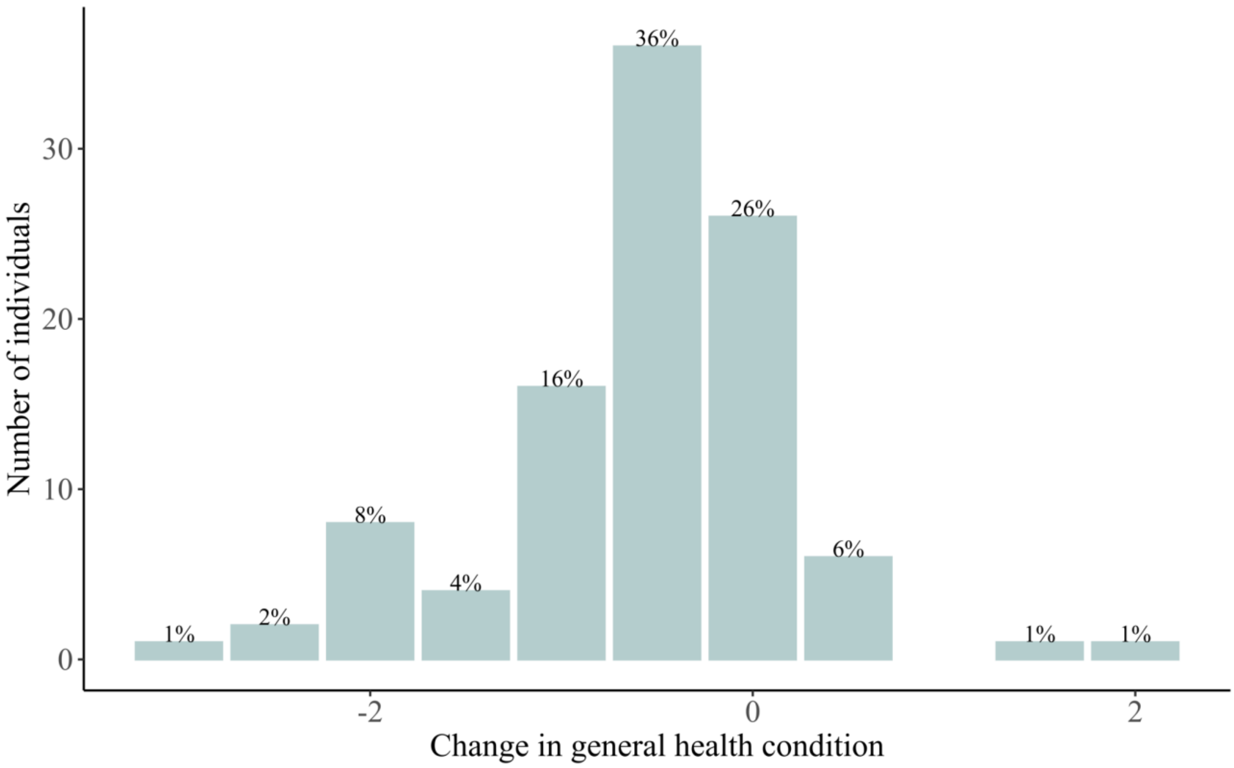

Figure 35: Distribution of inventoried trees according to classes of change in general health condition (*all2*). On the x-axis are the various classes of change expressed as *all2 -all1* (linear scala with 0 = dead, 4 = perfectly healty and with 0.5 increment) while on the y-axis is the number of inventoried trees.

The two monumental chestnut trees that exceed an improvement in general health condition of 0.5 points on the scale of the attribute considered here are the ID236 and ID214 chestnut trees. The first of these two specimens represent a special case already mentioned earlier in the text of this study, as it is embodied only by a sucker with a diameter of more than 30 cm. It is therefore not remarkable that in the second inventory its general health condition (*all2*) is estimated with a higher score than in the first inventory. The second chestnut tree (ID214) is not a special case like the previous one, its general health condition seems to have really improved compared to the first inventory. The tree in question has in fact grown especially in height (increase of 14.4 m in the last 20 years, the tree's height therefore reaches 32.4 m in the second inventory), thus increasing the volume of its crown remarkably.

This surprised new vitality was probably the result of the change in its location. Compared to the first inventory, the crown of the tree is in fact much less closed (*cclo1* vs *cclo2*), this change was probably induced by the removal by man of some trees around the monumental tree. The action was plausibly carried out to facilitate work on a road not far from the ancient chestnut tree. The increase in available light in the area where the monumental ID214 is situated is also reflected in the surrounding vegetation. In fact, the presence of the pioneer species *Ailantus altissima* was recorded, which is known for its rapid establishment and growth in environments subject to disturbance (in this case, vegetation removal interventions) (M. Conedera et al. 2014).

9% of the inventoried monumental trees slightly improved their health condition between the first and second inventory, while 25% of them did not change their score on the general health scale (*all1* = *all2*). Many of the surveyed chestnut trees, however, showed a slight deterioration (- 0.5), while the remaining 31% had a major decline in their general health condition (< -0.5). The most abrupt change in health was recorded by the monumental tree ID131, which went from an *all1* value of 3.5 to a health in the second inventory equal to 0.5.

There are several inventoried monumental chestnut trees that have suffered a decrease in circumference, 28 out of the total number of specimens still living in 2021. Of these 28 individuals, 19 have suffered both a decrease in girth (*cir2* - *cir1*) and in overall health condition (*all2* - *all1*). While nine individuals despite a decrease in circumference had a stable or increased *all1* value.

On the average, the chestnut trees analysed grew in height (*htree2* > *htree1*) by 1.78 m, the maximum growth in height was 14.4 m while the greatest decrease was 16.9 m recorded by tree ID78.

As the crown volume of the trees (*vcrow*) was not measured during the first inventory, there is no information regarding its change over time. Thanks to the derived attributes of the first inventory, however, details are available regarding the extent and severity of cracks present on the tree crown (*cc1* and *cc2*) and its more or less spatially balanced crown distribution (*cimb1* and *cimb2*). In general, it is observed that the canopy of monumental chestnut trees has deteriorated slightly over time while the crown observed in the second inventory tends to be more unbalanced (average *cimb1* in the first inventory is 2.04 while in the second inventory 2.24) and the extent and severity of cracks present in the crown has increased (from an average of 1.68 to 1.93).

The average crown closure (*cclo1*) of the analysed monumental trees decreases from 2.06 to 1.87. The hierarchical position of the crown of the monumental chestnut tree instead remains almost constant with an average in the first and second inventory of 1.48 and 1.58 respectively, the analysed specimens therefore remaining on average dominant over the surrounding canopies.

Analysing the lower part of the monumental chestnut tree and focusing on the trunk, the data show that the bark extension had a median of 3.0 (*barex1* values) in the first inventory, while in the second inventory it drops to 2.5 (*barex2* values). The health condition of the bark also decreased on average, although the median remains constant with a value of 3.0 (for both *barco1* and *barco2*). The attribute describing the degree of cavity of the trunk also increased on average, the median moving from 3.0 (*cav1*) to 3.5 (*cav2*). The mean collar activity (*bact1* and *bact2*) remained nearly stable with a value of 0.68 for the first inventory and 0.69 for the second inventory.

Below the information on the evolution of the structural compartments of monumental trees has been summarised in a simple and intuitive way (Tab. 21).

Table 21: Table with information on the evolution of the structural compartments of monumental trees

Attributes	Name	Trend
all1/2	General health condition	-
cc1/2	Extent and severity of crown cracks	+
cimb1/2	Crown imbalance	+
cclo1/2	Crown closure	-
cpos1/2	Hierarchical crown position	=
barex1/2	Bark extension	-
barco1/2	Bark health condition	=
cav1/2	Degree of trunk cavity	+
bact1/2	Basal suckers activity	=
tc1/2	Extent and severity of trunk cracks	+

Preforming a linear regression between general delta health condition (*all2-all1*) for all 101 surveyed chestnut trees shows a significant negative relationship between health development and crown imbalance (*cimb1*). In general, the trees that have undergone a negative change in overall health between the first and second inventory are now characterised by a larger trunk cavity dimension (*cav2*), lower bark health (*barco2*) and a larger portion of compromised crown (*vc*).

5.2.2 Geographical and environmental data over the last 20 years

So far it has been analysed how the general health of monumental trees has changed and how its structural compartments have evolved over the last 20 years. Not only does the tree as an individual evolve over time, but also its environment. In the following, it is therefore intended to report how it has changed over time. In particular, the forest cover in the area around the monumental trees and the substrate on which the tree grows. The forest cover was thus examined within a radius of 50 m and 100 m from the location of the inventoried monumental chestnut tree (Tab. 22).

Table 22: Table showing forest cover within 50 and 100 m of the investigated tree during the first and second inventories.

Radius	**Average percentage of area covered by forest**	
	2000s	2020s
50 [m]	57.18 %	56.04 %
100 [m]	62.02 %	63.44 %

The data show that within a 50 m radius from the monumental tree the average forest area decreased by slightly more than 1%, while at a 100 m radius it increased by 1.42%. The values of the attribute describing the crown closure of the inventoried chestnut trees (*cclo1* and *cclo2*) are in line with the trend within a 50 m radius, since, as reported above, on average the monumental chestnut trees underwent a crown opening.

Regarding the characteristics of the substrate where the monumental chestnut tree grows, the attributes *herb1, herb2, rock1 and rock2* were analysed (Annex 15 and 16). It emerges that 11% more of the individuals recorded now grow on a grass-free substrate, i.e. the substrate usually found under the forest. While 3% more are now found on grassland used as pasture for livestock (usually goats). This is at the expense of abandoned meadows (-8%) and managed meadows (-6%). Currently monumental chestnut trees are mainly found on a non-weedy substrate (39% of the monumental trees surveyed) and on a managed cut meadow (37%). Few of them, only 8%, are found on a wild, abandoned meadow.

Moreover, it is observed that trees with no or very low collar activity during the first inventory were, and still are, found in locations where the grassy layer is generally more managed ($p < 0.05$). It was also observed that the general health of the trees surveyed (*all1*) during the first inventory has a positive correlation with the herbaceous layer present 20 years ago ($p < 0.05$). Ten of the chestnut trees found dead were in places marked by *herb1* values <= 2. The presence of rock on the area around the monumental chestnut tree instead remained practically unchanged.

5.3 Management of monumental chestnut trees over the last 20 years, what are the results?

Our ancestors took care of the trees that have become monumental. Today, in many cases, these trees are abandoned, deprived of human care and management.

The management of monumental trees is often necessary to prevent their rapid deterioration (English Nature 2000). Other management motivations may be the preservation of the genetic heritage they represent, the maintenance of local traditional practices, and the perpetuation of the aesthetic, ecological and historical value of the landscape. In order to better understand the actual management situation of the monumental chestnut tree and the area in which it grows, several attributes have been used. They are grouped below according to the object they describe (Tab. 23):

Table 23: Grouping of attributes concerning management according to the described object.

Interventions on the monumental tree	Interventions on the surrounding area	Accessory signs of human activity	Geographic space
Cut of basal suckers	Liberation cut	Presence of hut	Built-up area around the tree
Deadwooding	Salvage cut	Use of tree cavity as storage	Distance to a road or a path
Thinning to reduce the crown size	Sanitation cut	Presence of ladder constructions	Valley
Pollarding	Clean	Discharge of materials around the tree	Municipality
Formative thinning cut	Other type of neighbour management	Other damaging activity	Location
Pruning intensity	Degree of selva management	-	-

The interventions on the monumental chestnut trees themselves refer in particular to interventions on the tree canopy and the removal of basal suckers. These two interventions were recorded during the fieldwork using the attributes *cutbas2* and *pru2*. An attempt was made to derive this two information from the first inventory, unfortunately with little success. The situation before the first inventory of the silvicultural interventions on these two parts remains within the ambit of this research therefore unknown (although for some specimens there is information in Krebs' notes in the first inventory (Krebs 2004).

5.3.1 Tree management

During the second inventory it was found that about 20% monumental chestnut trees had undergone sucker and basal shoot cutting (*cutbas2*, Fig. 36). In particular, 15.9% underwent punctual intervention for the removal of few basal suckers, while 4.9% interventions of moderate intensity and only 1.2% radical interventions.

The most of the specimens in the second inventory (excluding dead chestnut trees) did not undergo pruning. In contrast, the other chestnut trees (45.12%) were pruned mainly punctually (Fig. 36). However, there are 12 chestnut trees analysed which have been subjected to severe pruning in the last 20 years.

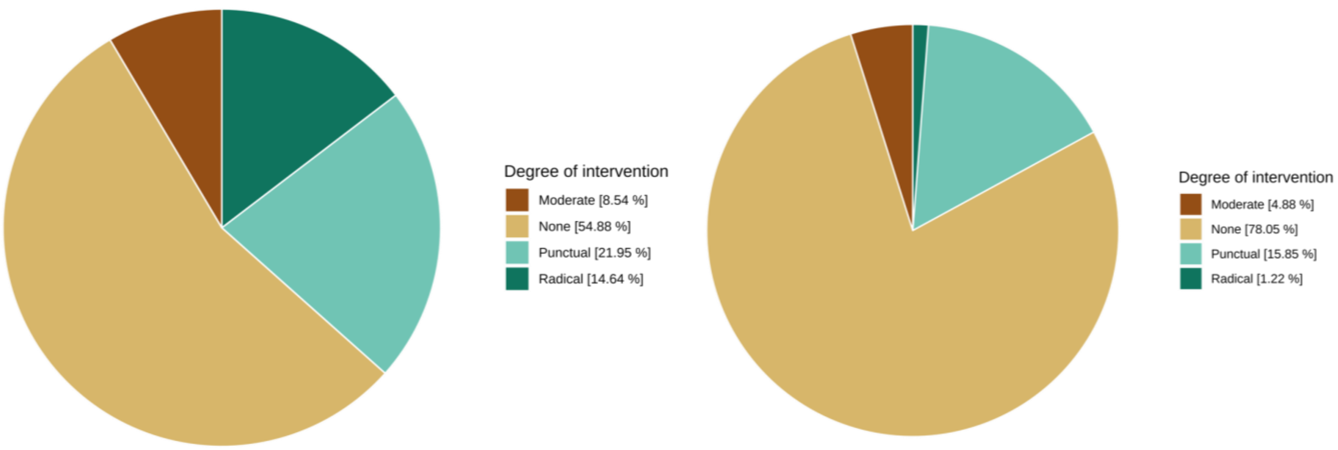

Figure 36: Pie charts depicting the degree of pruning of the canopy (attribute *pru2* on the left) and the degree of pruning of the basal suckers (attribute *cutbas2* on the right).

The *dwood2* attributes *red2, poll2* and *form2* were used to identify and characterise the pruning of the crown of the chestnut trees surveyed. It emerged that the trees that had undergone crown pruning in most cases were pruned with the aim to reduce their volume (*red2*). In contrast, radical pruning was often associated with pollarding (*poll2*). Only a few trees underwent other pruning measures. Pruning to shape the crown (*form2*) was found performed on 8 specimens, while the removal of dead branches (*dwood2*) was found on 9 specimens.

Analysing the interventions in the area around the monumental tree, it was discovered that for 57 monumental trees (69.51% of the inventoried individuals) the area was cleared of uncultivated vegetation (attribute *clean2*). For seven specimens only some trees (of variable diameter) were removed (attribute *lcut*). These are mainly little trees directly adjacent to the trunks of the monumental tree, but also larger trees, whose past presence is now testified by the cut stumps remaining on the ground. For three individuals the attribute *nother2* had a value of one, the interventions that could not be categorised in other attributes were pruning interventions on some adjacent chestnut trees (for two individuals) and the removal of a light pole for the chestnut tree with ID43. The attributes *salcut2* and *sancut2* never had a positive value, hence these interventions were never observed during the fieldwork.

Human influence and neglect in the management of the monumental chestnut tree could be also intuited through what happens on and around the monumental tree. The presence of a hut built in the crown, which is still intact, for example, can indicate a certain degree of care. Therefore, the attributes listed in the second-last column of Table 23 were also considered and analysed. In Krebs' inventory, 6.93% of the 101 specimens were characterised by the presence of a hut in the crown or in the trunk cavity (*hut1*). In the second inventory, the percentage dropped to 3.66% (*hut2*). Of many huts, only traces remain, for example a few nails or the presence of a wooden ladder on the trunk of the tree. Others were destroyed when the tree died (e.g. ID23 and ID40). The number of specimens with a ladder on their trunk decreased from 5 to 3, while the number of specimens with nails on their trunk remained almost stable in the two inventories (26 specimens in the first inventory and 27 in the second). The percentage of individuals, however, increases in the second inventory because the dead individuals were not analysed in this respect. The presence of nails is also usually accompanied by a cut/managed or grazed herbaceous layer (in the first and second inventory about 20 cases, $p < 0.01$). During the second inventory in the neighbouring area of 13 specimens there were some objects more or less abandoned, often piles of wood, wooden boards or iron wires. The presence of these types of objects around the tree has increased over the years (from 10 to 13 cases). On the other hand, the use of the tree cavity as a "storage room" especially for wooden objects has decreased. From the collected declarations, this decrease could be due to the growing awareness of the influence of accumulated wood (in tree trunks) and the danger of fire spread.

If a distinction is made between trees that in the first inventory were characterised by a positive value for any of the attributes in the penultimate column of Table 23 and trees that are apparently unaffected by the human hand in the terms described by these attributes, it becomes noticeable that in the case of the former, 5 out of 31 specimens, namely about 12.13%, died within 20 years. For all the others the percentage of dead chestnut trees is 27.45% (14 out of 51). The data collected thus shows that a chestnut tree that shows evidence of human presence has declined to death in lower percentage.

The index describing the degree of general management of the monumental chestnut trees analysed correlates negatively and significantly ($p < 0.001$) with many crown-related attributes. In particular, with the attributes *cclo2, cc2, cpos2, vc2* and *cimb2.* It also correlates negatively with monumental tree height (*htree2*), although with a lower significance ($p < 0.01$). The stability index of monumental trees is composed of two of these attributes (*cc2* and *cimb2*) and correlates positively with the general management index ($p < 0.001$). The more a monumental tree is managed and/or the area in which it is located is managed, the more the specimen indicates a high value of stability. The general management index, on the other hand, correlates negatively with the competition-index, so it appears that a specimen characterised by some kind of human management suffers less competition from surrounding trees. The performed analysis indicates in addition a positive relationship with the general health attribute *all2* and a negative relationship with the sucker collar activity (*bact2*).

5.3.2 Site management

The management level of the chestnut selva in which the monumental chestnut tree is located is described by the attribute *man*. For this attribute information on both the first and the second inventory is available. The level of management of the chestnut selva where the *monumental* tree is located has increased for 10% of the individuals in the last 20 years, but at the same time for 8% of the surveyed chestnut trees there has been an abandonment of management (Annex 17). It would seem, that there has been a polarisation of the values of this attribute between the first and the second inventory. While 20 years ago the tendency was a minimal management of the forest in which the monumental tree was located, today the same forest is either managed or abandoned. The middle ground has in fact decreased by 19%. The attribute *man2* subjected to a linear regression with the attributes contained in this study shows many correlations. In particular, it is noted that the management of the chestnut forest is negatively correlated with the attribute *slo20/10* ($p < 0.001$); the steeper the terrain in which the tree analysed grows, the less the forest seems to be managed. This observation could be related to the greater technical difficulty in managing a forest in steep terrain. In addition, the more built-up the area around the monumental chestnut tree is (attribute *bu50*), the greater the forest management seems to be ($p < 0.001$). This feature could be interpreted in the same way, forest management could be easier where there are settlements that can support silvicultural practice. The presence of nails on the trunk of the monumental chestnut tree is also more significant when the forest is managed ($p < 0.001$). The higher occurrence could indicate a greater overall human influence on the chestnut area, which could also be reflected in the degree of management of the chestnut forest.

6 Discussion and conclusion

6.1 Premise

The amount of information collected and available to answer the three main research questions is rather wide and provides a first basis for future research in different fields. Although the many attributes, the number of individuals analysed (82 living and 19 dead trees) is relatively low and should be strengthened in the future by the census of other monumental chestnut trees (to be continued with the census of the remaining chestnut trees from the first inventory). The discussion has been divided into four main parts. The indices constructed will be discussed first and afterwards the discussion will follow the order of the research questions.

6.2 Indexes discussion

A general point that needs to be raised that applies to all indices is the use of weighting factors in the calculation of values. An attempt was made to ponder some attributes within the indices in order to better represent reality. These factors are the result of considerations based on observations and/or acquired knowledge. These were discussed and optimised in consultation with experts (Co-supervisor Marco Conedera and Advisor Patrik Krebs). In order to have an even more solid basis, the weighting of attributes should be based on observations and results of scientific studies (statistical and empirical basis). Research should be conducted in the future to refine these factors and to be able to assess the accuracy of the weighting factors proposed in this study.

6.2.3 Health index

The main purpose of the health index was to obtain a more comprehensive and precise index that would more accurately represent the current health condition of the tree. The attribute general health condition (*all2*) and the health index give similar and relevant values for each individual (see chapter 5.1). However, a great variability of the health index in the case of tree individuals having 0.5 as *all2* value is observed (Fig. 21). This could be due to the larger number of observations for this health category or the difficulty and consequent variability in assigning this value in the field. A factor that should not be underestimated is the use of crown volume (*vcrow*) as a component of the health index. Crown volume can in fact sometimes be misinterpreted. After a severe pruning or the collapse of a large part of the crown, the volume is drastically reduced, but this does not necessarily mean a massive net loss of vitality. Often, even with the loss of a large canopy volume, the tree can retain or even increase its vitality and then demonstrate the ability to rebuild the lost volume. An example is specimen ID236 represented only by a sucker, which produces a small crown (compared to monumental trees) and is disadvantaged within the health index, but in fact embodies good general health. A possible alternative to adjust the health index would be to give more weight to the compromised and missing crown volume (*vm* and *vc*) by fixing the mathematical formula used in this study. In this way, a recently pruned, thus reduced and probably more vigorous, vital and dense canopy would be better represented. Another option would be to add an ordinal attribute describing the general health of the crown volume, as for example done for bark health conditions (*barco*). The mathematical formula used in this study to calculate the health index values would therefore contain a new parameter that influences the volume of the crown according to its health condition. The introduction of this new attribute, however, would require its value to be assigned in those seasons when the tree has leaves. By doing so, the vitality of the crown would be better assessed. Multiple attributes describing the health of the canopy could also be introduced and it might be important to also consider diseases that may afflict it and thus affect its health. If new attributes were to be added to describe the canopy, it would then be necessary to understand through a specific study the utility of employing the attributes missing and compromised canopy volume (*vm* and *vc*). The general health condition attribute (*all2*) in this study is better able to reflect the health condition of individuals since other parameters are consciously or unconsciously considered on site which the health index fails to capture.

The volume of the crown (*vcrow*) was calculated in this study by assigning each specimen a solid geometric figure (*geo*). To simplify and speed up data collection one could think of arbitrarily choosing the conical geometric figure (most frequently found in this study). There are also other methods for calculating the volume of a tree crown, more information can be obtained through the review published by Zhu et al. (2021). However, these methods require advanced technological equipment and are not always suitable for trees located in the forest.

6.2.2 Competition index

The majority of the existing literature has so far concentrated on trees of a size and age within the range of economic use of the tree (Fay 2002). The competition experienced by a tree of extraordinary size and age is probably not the same as that experienced by a young or mature tree. In the scientific literature, there are no references or studies of the competition suffered by monumental trees, so an attempt has been made in this report to describe such competition by means of the attributes belonging to the competition group and weighting factors.

In this study the research area of the competitors and the choice of individuals to be recorded was arbitrarily defined up to and not beyond 15 meters from the trunk of the tree and a maximum of eight competitors were recorded. Sometimes, however, the competitors were more distant and more than eight; moreover, it could happen that behind a competitor with a low degree of competition with respect to the monumental chestnut there was another larger and/or more competitive one (the most frequently encountered situation was that of the presence of a hazel near the trunk of the tree surveyed not far from a tree with a larger diameter, such as a birch or a chestnut). The choice of recording competitors closer to the trunk should perhaps be revised and priority could be placed only on the most relevant competitors for the monumental chestnut. An alternative would be to record only those competitor trees that are in contact with the canopy of the surveyed tree, thus reducing the number of records and hence the effort and time in the field; however, a negative aspect of this alternative would be the difficulty in identifying canopies that overlap with the surveyed tree during the leafless winter period. If, on the other hand, a study was to be conducted specifically on the competition suffered by monumental trees, one might consider investing more time in fieldwork and record all competitors within a predefined radius. The search radius should in any case be defined by assessing the impact of the competitor tree on the specimen under analysis.

To better complete the competition index, one could also consider including the slope of the land where the surveyed tree is located and the exposure of the slope in the formula used to calculate it. To better complement the competition index proposed in this study, consideration could also be given to including the slope of the terrain where the surveyed tree is located and the exposure of the slope in the formula used to calculate it, as well as the measurement of the height of the competing trees. This would allow competition for light to be better included. In this research, the height of the competitor trees was not measured, but it is partly contained in the diameter class of the competitor (*dbhX*).

6.2.3 Stability index

The stability index in this work was designed and created during the analysis of the data and its construction was forged by the need to integrate an attribute capable of gathering several structural characteristics of the tree into a single attribute (Chapter 4.4.1). The attributes degree of trunk cavity (*cav2)* and the extent and severity of trunk cracks (*tc2*) were investigated in depth to better understand whether they should both be included and what contribution they could make to the index. It was found that the attribute *cav2* is positively closely related to the cracks on the monumental trunk (*tc2*). However, it has been found that *tc2* is more significant and can give more complete information on the degree of stability. Indeed, depending on the tree's reaction to the cavity, the trunk shows more or less severe cracks on the rest of the trunk. Based on these observations, it was ultimately decided to include only *tc2* in the construction of the stability index. The degree of trunk cavity, however, could be included in a new index formulation. In that case, however, it would be necessary to define the degree of trunk cavity more rigorously through more precise analyses in the field. For instance, the percentage of cavities of the total trunk volume could be measured. To be even more precise and complete in assessing the influence of the cavity on the tree structure, the weight of the crown that must support the tree trunk should also be taken into account. In the analysis it also emerged that the attribute describing the slenderness (*slender*) should be included. This choice was initially discarded because it was assumed that, since the diameter of the tree was very large and hence also very similar, its influence could be minimal. On the other hand, investigating the tree height (attribute *htree2*) it was found that the height of the different individuals is very variable and that therefore the slenderness value could provide the index with very valuable information.

The stability index could be implemented by evaluating the root system of the tree, a feature not considered in this study, but which could have a considerable influence on the overall stability of the tree. Analysis of the causes of death of monumental trees that have died in the last twenty years has in fact often revealed a reduced (flat) root system, which may be implicated in conjunction with other factors in the collapse of the trees in the survey. Attributes describing the extent and severity of cracks in the crown and trunk could also be accompanied and implemented by a description of the cracks and their classification, characterization, e.g. by following Mattheck (2007) in his field guide for visual tree assessment.

6.2.4 Management index

The management index is perhaps in this research the index that would most need adjustment and implementation. In the formulation of this index, considerable importance is given to the pruning of the crown and basal suckers, while the management of the space around the tree and the forest is less weighted and considered. There is therefore an urgent need to research, possibly empirically, the degree of influence that different management measures have on the monumental tree.

In the index constructed in this study, the herbaceous layer of the area where the recorded specimen is located (*herb*) could be integrated. In fact, it not only describes the environment in which the tree is located, but also gives an indication of the degree to which the herbaceous layer is managed.

6.3 Q1 discussion

The first research question Q1 focuses on the present conditions of a part of the monumental chestnut trees surveyed by Krebs during the first inventory (Krebs, 2004). Today, 80% of these trees have a general health (*all2*) of less or equal to 2 (maximum score of 4). The data analysis shows a positive relationship between general health (*all2*) and the stability index but a negative relationship between general health and the competition index. The competition index on the other hand appears to be in a negative relationship with the stability index. The extension and health conditions of the bark (*barex2* and *barco2*) are not much reduced compared to an optimal situation. Despite this, the extension and severity of the cracks present on the trunk are quite severe and widespread. The crown has often an unbalanced structure (*cimb2*) with cracks of medium severity (*cc2*) and a hierarchical position between dominant and co-dominant (*cpos2*). A distinguishing feature of almost all of these trees is the presence of collar activity (*bact2*). In this study, the basal suckers activity of the collar correlates positively with the degree of crown cracks (*cc2*, $p < 0.01$). This relationship can be explained by the tree's attempt to compensate for a weakened crown due to the extent and severity of the cracks. It is in fact the collar that has the greatest potential for the production of a secondary trunk and from a physiological perspective can be considered a specialised rejuvenation organ (Tredici 2001). Another distinguish feature of the surveyed trees is the very high degree of trunk cavity with a half of the specimens having an index of cavity equal to or greater than 3.5 (*cav2*). In ancient stage cavity is often determined by a process that we could call centrifugal decay, that is the spread or expansion of rotten wood and cavities starting from the older growth rings which are located next to the pith and closer to the soil. In some cases, inside the cavity, moist and fertile litter and soil may accumulate promoting the formation of new suckers and thus recolonisation of the hollow (Dujesiefken et al. 2016). In the second inventory there were cases in which the basal suckers recolonise the trunk cavity. Examples are given by tree ID43 and ID63 (Annex 18). Trunk cavity has often been considered a predominant feature antagonistic to the longevity and health of a tree (Dujesiefken et al. 2016), a trend also visible in this study, where the degree of cavity (*cav2*), negatively correlates with the general health condition (*all2*) and the health index (both $p < 0.001$). However, when it promotes rejuvenation, it cannot be considered merely a sign of senescence, but also an opportunity to counteract it.

Conventionally, the life of a tree is considered to be a linear process. From the seed, the organism develops, grows, and matures, ending up in its death (if other external factors do not drastically affect its vitality beforehand). Dujesiefken et al. (2016) distinguish in their work three main stages in the life of a tree, namely younger stage, mature stage, and ancient stage. The trees inventoried in this research belong to the ancient stage which we are about to define and characterise. The main energy investments during the mature stage are in increasing the available leaf area, and in verticalization of the trunk (Dujesiefken et al. 2016). As the tree gets older, however, apical dominance begins to weaken, and this is reflected in the increase in ramifications. Over time, the branches start to assume a certain autonomy and compete with each other. In the transitional stage between the mature and ancient stage the canopy begins to round off and gradually loses vitality especially in the peripheral areas. The ancient stage of a tree is generally characterised by retrenchment and decay of the crown, and also of the root system.

The trunk of a tree in this life stage is often affected by cavities, the formation of functional units (semi-autonomous units) and reiterative growth is apparent and fortified. In this study the presence of these characteristics was supported by the observation and assessment of the missing and compromised crown volume (*vm* and *vc* corresponding in both cases to an average of 22%), the very pronounced trunk cavity (*cav2*) and the presence of basal (*bact2*) and in-canopy suckers shoots (the latter not recorded but observed in the field).

To better understand the phenomenon of functional units, one must evoke the model proposed by Shigo and its development into the model commonly called CODIT (acronym for compartmentalisation of decay in trees) (Shigo 1985; Fay 2002; Smith 2006). This model places the tree's propensity for compartmentalisation as a fundamental basis (Dujesiefken et al. 2016). It is a defensive process in which boundaries are formed in order to isolate injured/damaged tissue and the subsequent possible spread of pathogens (Smith 2006; Shigo 1985). A centuries-old tree such as a monumental tree has, over its lifetime, suffered various mechanical damages due to different factors (environmental, human, etc.), and as the years go by, its decay becomes more extensive. These scars and signs of ageing are reflected in its morphological appearance and expression of functional units (for additional information see Lonsdale 2013). Specimens ID239 and ID247 show quite clearly the phenomenon of compartmentalisation to marginalise the dacay process to the whole organism (Fig. 37 and Annex 19).

Figure 37: Photograph of the lower trunk of trees ID239 (on the left) and ID247 (on the right). It can be seen that part of the trunk is affected by decay and that this part has been excluded by compartmentalisation. The damaged section is quite distinguishable from the remaining trunk and its subsequent collapse can be anticipated.

In some cases, there is a clear division of the trunk and it appears that the individual consists of two completely independent compartments, occasionally it appears that the monumental tree consists of several individuals (a very clear example is given by specimen ID133 and specimen ID238 (Annex 20 and 21). The phenomenon of functional units allows the preservation of some compartments at the expense of others; the segregation and loss of dysfunctional sections can be interpreted as a survival strategy. In the second inventory, some examples of preservation of the organism at the expense of the loss of certain compartments were observed. An example is given by individual ID133 (Annex 21), which despite having lost almost a third of its total trunk and crown volume is still alive (general health condition *all2* = 1). The loss of some compartments to safeguard others has not yet been addressed in depth in the scientific literature in the context of monumental and ancient trees. The presence of more than 300 monumental chestnut trees (belonging to the ancient stage of life) on the territory of Italian-speaking Switzerland therefore represents a unique opportunity for future research on this topic. The creation of 3D models of the lower part of the trunk also makes it possible to document in detail the development of compartmentalisation and its influence on the structure. Since the loss of parts of the tree is a frequent feature in many of the trees examined, it would be interesting to further study the role that this loss could play on the relief induced by the tree losing part of its weight and on the development of longevity.

The competition index has allowed this research to obtain an insight into the current competitive situation of the monumental tree in the three upper valleys (Leventina, Blenio and Riviera) of Ticino. It was possible to determine first which species grow around the surveyed tree, but also to investigate the extent of competition with respect to eight cardinal sectors. The species most present that exercises the greatest degree of competition was the chestnut tree itself. This result did not surprise expectations, since almost all the trees surveyed are located in a selva. The competition index was found to be in a (negative) relationship with the attributes describing health status (*all2*), a relationship also found in the literature (Fay 2002). However, it was also found to be in a (negative) relationship with the management index, suggesting a possible management intervention to counteract competition and thus support the health status of the trees surveyed. The competition index was also found to be in an even more significant negative relationship ($p < 0.001$) with the stability index, perhaps suggesting a possible improvement in the health of monumental trees through increased stability of the structure supported by the removal of competing trees.

6.4 Q2 discussion

The second research question addressed the evolution of the characteristics found in Q1 over the last twenty years (i.e. between the first and the second inventory). Nearly one third (30%) of the surveyed trees alive display a current health status equivalent to 0.5 on the *all2* attribute scale (maximum score 4). A very low score that intuitively makes it seem like a bitter fate lies ahead. However, analysing the trend over the last twenty years and considering what has been discussed so far, it is legitimate to hypothesise the action of processes that could counteract the senescence process, and thus, delay the time of death. Crown and root retrenchment (a process of size reduction) is a characteristic of the monumental trees (Ibrahim 2004). This phenomenon usually starts when the root system can no longer cope with the energy requirements of the canopy and weakens (Dujesiefken et al. 2016). The root system is thus often colonised by fungi and the decay progresses to affect hartwood (cavity formation). These processes are commonly believed to be indications of senescence and a course of decline leading to death; however, studies (Fay 2002; Ferrini 2006; Dujesiefken et al. 2016) have shown the complexity of these phenomena and the possible misinterpretation of the course of a tree's life development (especially on short-term observations). Crown retrenchment can be counteracted by the ability to build new crown through the stimulation of dormant and adventitious buds on the trunk and branches of the tree. The process that counteracts senescence is called rejuvenescence and allows the tree to go through new stages of its life cycle. In this study, the change in crown volume could not be assessed as this measurement was not carried out during the first inventory. The height of the tree, however, has increased on average (+1.8 m) over the last twenty years, so an increase in crown volume could also be assumed for some individuals. It is therefore possible to hypothesise a process of rejuvenescence within the study data, specifically a rejuvenation of the crown in the middle of the senescence process.

Nearly a fifth (18.81%) of the trees surveyed died during the last two decades and the main cause of death was tree collapse probably due to environmental factors. Two-thirds (66.37%) suffered a deterioration in their general health (*all1/2*), while 34% maintained the same or even improved health. Over time, most of the surveyed trees experienced a decrease in bark extension (*barex1/2*), the trunk cavity enlarged (*cav1/2*), while the basal activity of the collar (*bact1/2*) remained on average the same. On average, the crown of the tree had an opening (*cclo1/2*) although its hierarchical position (*cpos1/2*) remained the same. The main differences between surviving and perished individuals were found in crown imbalance (larger for the dead), hierarchical crown position (more suppressed for the dead) and basal collar activity (higher for the survivors) during the first inventory. The attribute from the first inventory that seems to have most influenced the health status trend was the imbalance of the crown (*cimb1*). The most pronounced differences visible in the second inventory for the surviving trees with respect to their health status trend (worsened, stable) were found in the degree of trunk cavity (*cav2*), bark health condition (*barco2*) and the portion of the crown that was compromised (*vc*). Over the past 20 years, 11% more individuals analysed are found on terrain typical of woodland (shift from grass-covered terrain to terrain where the grass layer is absent, typically woodland), while 3% more on a grassland used as pasture (shift from ungrazed to grazed land). The health of the monumental trees recorded in 2000 also correlates with the herbaceous layer of the first inventory (general health condition *all1* was in fact higher when the monumental tree was located on a meadow kept by people, or used for grazing purposes *herb1*), the latter of which was also found to be in a negative relationship with collar activity (*bact1*).

It was interesting to find differences in the collar activity values of the first inventory between dead and surviving individuals, as the specimens that subsequently died tended to have on average lower collar activity (Chapter 5.2). It could be hypothesised that the capacity of the collar and thus of the rejuvenescence process to counteract the senescence process has been exhausted and that the specimens subsequently died. Two other attribute that distinguishes surviving from dead chestnut trees are crown imbalance and crown hierarchical position (*cimb1, cpos2*), the individuals that died in the last two decades were thus characterised by a strong canopy imbalance and a subordinate hierarchical position, features significantly negatively associated with tree stability index. If a statistical model capable of predicting the survival chances of monumental chestnut trees is produced in the future, these three attributes (*bact, cimb, cpos*) must be considered and integrated. From the results obtained, tree instability and thus structural collapse played in fact an important role in the causes of death of monumental specimens. To obtain a more complete model, however, one would have to introduce parameters that measure the health of the hidden side of the tree (i.e. the root system).

It has been observed that the process of senescence can be counteracted by various processes and that the health of one third of the individuals (see above) over the last 20 years has remained the same or even improved. Despite this, 19 deaths were recorded out of 101 individuals surveyed. If there are no substantial changes in the causes of death and in the environments, one could speculate on the extinction of the 82 remaining monumental trees in the study area within a century. The senescence process is not linear, so this type of extrapolation is more complex than a simple statistical calculation based on observing the survival rate over 20 years of 101 individuals. However, it does raise awareness of the urgency of carrying out research related to these centenarian individuals and the need to act if attempts are to be made to preserve these trees for longer. A systematic census should also be started on future monumental trees, i.e. those trees that do not yet reach 7 m in circumference, but are close to it. Recording this information would provide a more complete understanding of the population dynamics of monumental chestnut trees in Ticino and the Moesano. The question must also be asked about the definition of monumental trees, and therefore whether to register those individuals that are in the ancient stage, but due to partial trunk collapses do not reach 7 m in circumference. These should indeed be included if one wants to investigate the senescence and rejuvenation process of trees in the ancient stage.

6.5 Q3 discussion

The third research question concerned the management measures carried out on the monumental chestnut trees surveyed and their effect on the organism. Almost half of the trees (45%) underwent crown pruning, mostly punctual and mainly aimed at reducing their volume. Only 20% of the trees have undergone pruning of the collar suckers in the last 20 years. The area around the majority of trees (70%) has been cleaned up (removal of dead branches, bushes, etc.). The selva in which the specimens are located has experienced a polarisation of the management carried out, with a tendency to be either managed or abandoned (attribute *man1/2*). In past years the middle ground was more present. The management of the selva around the tree is also influenced by the terrain slope and the distance from built-up areas. The general management of the tree and the area in which it is located (management index) mainly influence the closure and hierarchical position of the canopy, the severity and extent of cracks in the crown (*cc*), the compromised volume of the crown (*vc*) and its imbalance (*cimb*). The management index was also found to correlate positively with the general health (*all2*) and the stability index and negatively with the competition index.

Reiterations, a process belonging to rejuvenescence (which include collar activity), are the development of new shoots or axes and even whole branch systems that can be caused by a change in the environment or sudden damage (Fay 2002). Collar activity can to some extent and in some cases be stimulated by tree management. Pruning in general induces an important change in the distribution of resources within the tree and can in some cases create disproportions in the depletion of reserves in certain areas of the tree (Shigo 1985; Clair-Maczulajtys et al. 1997). It can also induce younger buds to form new shoots (Ferrini 2006), which in some cases can positively influence tree longevity. However, the excessive production of new vegetation can strongly reduce reserves and nutrients (Ferrini 2006; Clair-Maczulajtys et al. 1997), and can also have negative repercussions (Shigo 1985; Fay 2002). Trees in the second inventory are mostly characterised by punctual pruning, which is also recommended in the literature (Ferrini 2006). In order to ensure a positive influence, pruning of trees at a later stage of maturity and in ancient stage should be limited to eliminating dead parts of the tree, structurally weak parts or parts (branches) that horizontally unbalance the tree (Lonsdale 2013b; Ferrini 2006). The removal of these parts should not exceed 10-25% of the total number of branches per year (Ferrini 2006; English Nature 2000). Crown reduction should also be performed when a viable "inner" crown is present (Lonsdale 2013a), like for example ID134 (Annex 22). In this case, even if the pruning would seem severe, the remaining portion can provide a dense and vital crown after pruning. The relationship between the removed leaf portion and the tree reaction in terms of vitality and vigour is, nevertheless, difficult to predict especially in the long term. Excessive removal may show an initial vigour of the tree, but with time a weakening that may lead to the tree becoming more susceptible to frost and infection (Clair-Maczulajtys et al. 1997).

Studies show that in old trees that have been pruned in the past (commonly referred to as “pollards[2]”) the functional units are more and better observed than in the same species that have not been pruned or only slightly pruned ("maidens") (English Nature 2000; Dujesiefken et al. 2016). It would also seem that maidens live less long than pollards because when they suffer damage or failure of a single stem, the whole tree system is more likely to collapse. Compartmentalisation is therefore a fundamental strategy for the chance of ageing in the monumental trees. For this reason, knowledge

[2] Pollards is a tree pruned like a coppice but above ground level (English Nature 2000)

of the past history of interventions/pruning and recognition of functional units can help achieve pruning that supports tree vitality and longevity and should guide decision-making in tree management (Ferrini 2006).

The results of the present study brought to light the negative relationship between the management index and the competition index, which is not surprising. However, the decrease in competition through the removal of rival trees must be conducted with caution and premeditation. The exposure of the monumental tree caused by the removal of neighbouring trees can lead to deformation, and failure of some parts (even under normal wind conditions).

6.5 Concluding remarks

In century-old and monumental trees, the phenomenon of decay is very complex and still little studied (Lonsdale 2013). The tree that is observed in the field is in fact the result of hundreds of years of interaction between the tree, the environment, and other organisms. This study and the collection of attributes in the field allow a more extensive knowledge and understanding of trees in the ancient stage, laying the foundations for new research work. The data collected as part of this study should be strengthened with the continuation of the second inventory and thus the addition of new data. It would also be appropriate to collect additional information on the management history of each individual. This process should be accompanied by the acquisition of oral sources and testimonies about the period of intervention, intensity, and purpose. Recognition and recording of functional units that appear visible or intuitable should furthermore be included. This would provide a more solid basis for future management interventions and the role of these units in the survival strategy of monumental trees could be further investigated. It would then be interesting to be able to compare the results with other species that have become monumental and also try to understand the role of the species itself in the formation of functional units and its role in the longevity path.

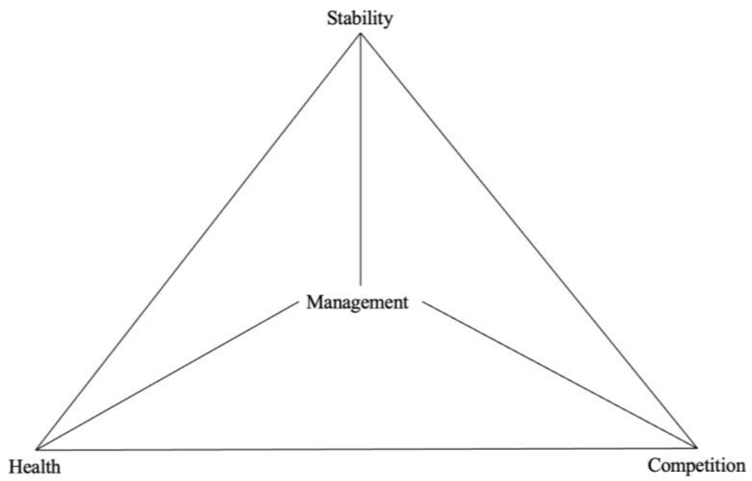

Figure 38: Network of relationships between management, stability, health, and competition.

It emerged from the results and discussion of this study that the degree of management is a fundamental starting point for the conservation of the tree heritage represented by monumental chestnut trees (Fig. 38). An increase in management can in fact have a positive influence on the competition suffered by the tree (decreasing the competition), on the health and on the stability of the tree; the latter in turn also positively influences the health of the tree. More effort and resources in management at a given point in time lead to less effort and resource use in the future. In fact, increasing the degree of management improves the health of monument trees that will need less care in the future (when they will also be more susceptible). Therefore, it is important not to abandon the management of these trees (especially of individuals that are not yet monumental, pools of potential monumental trees) if we want to preserve them. They embody a legacy passed on to us by our ancestors over time, and not only that, they also play an important role in the promotion of biodiversity and nature conservation (English Nature 2000).

7. Literature

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8. Annex

Annex 1

Figure 1: Portion of the inventoried trees in the three valleys of the study area. On the y-axis is the percentage of trees inventoried in the second inventory compared to the total inventoried in the first inventory while on the y-axis are the three valleys.

Annex 2

Table 1: Summary table of attributes used for the analysis. The table contains the label, name, date type, number type, unit of measure, category (according to Fig. 6 of the main document), and values for each attribute.

	Label	**Name**	**Data type**	**Number type**	**Unit**	**Cat.**	**Values**
Tree data	*cir*	Trunk circumference at breast height	cardinal	floating	m	1+2	-
	dbh	Diameter at breast height	cardinal	floating	m	1+2	-
	htree	Tree height	cardinal	floating	m	1+2	-
	slender	Slenderness coefficient	cardinal	floating	-	2	-
	htrunk	Trunk height	cardinal	floating	m	2	-
	hcb	Crown base height	cardinal	floating	m	2	-
	cth	Crown thickness	cardinal	floating	m	2	-
	d1/d2	Crown diameter	cardinal	floating	m	2	-
	da	Average crown diameter	cardinal	floating	m	2	-
	geo	Geometric figure of the crown	descriptive	string	-	2	Sphere Ellipsoid Cylinder Cone Paraboloid
	vm	Missing crown volume	cardinal	floating	-	2	-

vc	Compromised crown volume	cardinal	floating	-	2	-
vcrow	Crown volume	cardinal	floating	m^3	2	-
cpos	Hierarchical crown position	ordinal	floating	-	1d+2	0 = Open grow 1= Dominant crown 2 = Co-dominant crown 3 = Intermediate crown 4 = Supressed crown
cclo	Crown closure	ordinal	floating	-	1+2	0 = Free crown 1 = ¼ Surrounded 2 = ½ Surrounded 3 = ¾ Surrounded 4 = Closed crown
barex	Degree of bark extension	ordinal	floating	-	1+2	0 = Completely debarked trunk 1 = Bark cover ¼ of the circumference of the trunk 2 = Bark cover ½ of the circumference of the trunk 3 = Bark cover ¾ of the circumference of the trunk 4 = Bark cover the full circumference of the trunk
cav	Degree of trunk cavity	ordinal	floating	-	1+2	0 = Apparently Free of cavity 1 = ¼ of the maximal cavity 2 = ½ of the maximal cavity

						3 = ¾ of the maximal cavity 4 = Maximal cavity
cc	Extent and severity of crown cracks	ordinal	floating	-	1d+2	0 = No visible cracks in the crown structure 1 = Few, minor cracks on the crown structure 2 = Some areas of the crown structure are characterized by (not too severe) cracks 3 = Severe cracks on one or more portions of the crown structure 4 = Severe cracks on the entire crown structure
tc	Extent and severity of trunk cracks	ordinal	floating	-	1d+2	0 = No visible cracks 1 = Few, minor cracks 2 = Some areas are characterized by (not too severe) cracks 3 = Severe cracks on one or more portions 4 = Severe cracks on the entire crown structure
barco	Bark health condition	ordinal	floating	-	1d+2	0 = Very weak bark, Functionality of the bark is not assured 1 = Tree bark with weakened and/or partly not intact functionality on most of the trunk 2 = Tree bark with some weakened or/and

						partly not intact functionality 3 = Firm and vital tree bark on most of the trunk, only a few signs of weakening. 4 = Firm and vital bark with clear signs of full functionality
cimb	Imbalance of the crown	ordinal	floating	-	1d+2	0 = Stable, well-distributed and balanced crown 1 = Between stable and slightly unstable crown, it is unevenly distributed in space 2 = Slightly unstable and unevenly distributed crown 3 = Clear structural imbalance of the crown that could compromise the structure stability of the tree 4 = Strong structural imbalance in the crown. Branches not uniform distributed, with ramifications too extensive to guarantee plant stability
bact	Basal suckers activity	ordinal	floating	-	1d+2	0 = No activity/ proliferation 1 = Moderate activity/ proliferation

						2 = Important activity/ proliferation
all	Degree of health condition	ordinal	floating		1+2	0 = Dead 4 = Perfectly healthy
dclass	Dead class	ordinal	integer	-	2	1 = Tree still standing, almost all branches are dead but still attached to the structure 2 = Tree still standing, only main branches still present 3 = The tree has crashed to the ground and in some parts of its trunk the bark is still present. 4 = The tree has crashed to the ground; trunk debarked and only a few structures are still recognizable. 5 = Dead trunk still standing (usually the lower part) 6 = Nothing remained
dex	Dead explanation	ordinal	integer	-	2	1 = Environmental causes 2 = Human causes 3 = Environmental and human causes
nails	Presence of nails	ordinal	boolean		1d+2	0 = Absence 1 = Presence
marks	Presence of painted marks	ordinal	boolean	-	1d+2	0 = Absence 1 = Presence

	hut	Presence of huts	ordinal	boolean	-	1d+2	0 = Absence 1 = Presence
	stor	Use of tree cavity as storage	ordinal	boolean	-	1d+2	0 = Absence 1 = Presence
	ladd	Presence of ladder constructions	ordinal	boolean	-	1d+2	0 = Absence 1 = Presence
	disc	Discharge of materials around the tree	ordinal	boolean	-	1d+2	0 = Absence 1 = Presence
	dother	Other damaging activity	ordinal	boolean	-	1d+2	0 = Absence 1 = Presence
	SI	Stability index	cardinal	floating	-	2	-
	HI	Health index	cardinal	floating	-	2	-
Geographical and environmental data	*lon*	Longitude	ordinal	integer	-	GIS	-
	lat	Latitude	ordinal	integer	-	GIS	-
	alt	Altitude	ordinal	integer	m.a.s.l.	GIS	-
	slo20/slo25	Slope	ordinal	floating	s.d.	GIS	-
	N10/N40	Northness	ordinal	floating	-	GIS	-
	valle	Valley	descriptive	string	-	GIS	-
	mun	Municipality	descriptive	string	-	GIS	-
	loc	Location	descriptive	string	-	GIS	-
	dpath	Distance to a path	cardinal	floating	m	GIS	-
	droad	Distance to a road	cardinal	floating	m	GIS	-

	bu50. bu100	Built-up area around the tree	cardinal	floating	m^3	GIS	-
	dist20r20	Distance to forest area	cardinal	floating	m	GIS	-
	forXr20, forYr50, forYr100	Forest area	cardinal	floating	m	GIS	-
	herb	Herbaceous layer	ordinal	floating	-	1d+2	0 = No herbaceous layer 1 = Abandoned/wild meadow 2 = Managed/cut meadow 3 = Pasture/grazed meadow
	rock	Degree of rock cover	ordinal	floating	-	1d+2	0 = Absent 1 = Modest 2 = Medium 3 = Nearly complete
Competition data	*aspX*	Cardinal sector	descriptive	string	-	2	N = North NE = North-east E = East SE = South-east S = South SW = South-west W = West NW = North-west
	specX	Competitors species	descriptive	string	-	2	-
	distX	Distance to competitor tree	cardinal	floating	m	2	-
	dbhX	Diameter class	cardinal	floating	-	2	1 = <12 cm 2 = 13-30 cm 3 = 31-40 cm

							4 = 41-50 cm 5 = 51-100 cm 6 = >100 cm
	CI	Competition index	cardinal	floating	-	2	-
			Tree collar pruning				
Management data	*cutbas*	Cut of basal suckers	ordinal	floating	-	1d+2	0 = No intervention 1 = Punctual intervention 2 = Moderate intervention 3 = Radical intervention
			Crown pruning				
	dwood2	Deadwooding	ordinal	boolean	-	2	0 = Absence 1 = Presence
	red2	Crown thinning to reduce crown size	ordinal	boolean	-	2	0 = Absence 1 = Presence
	poll2	Pollarding	ordinal	boolean	-	2	0 = Absence 1 = Presence
	form2	Formative/shape thinning cut	ordinal	boolean	-	2	0 = Absence 1 = Presence
	pru	Pruning intensity	ordinal	integer	-	1d+2	0 = No intervention 1 = Punctual intervention 2 = Moderate intervention 3 = Radical intervention

Site Management						
man	Degree of selva management	ordinal	integer	-	1d+2	0 = Abandoned selva 1 = Minimal selva management 2 = Managed restored selva
lcut	Liberation cut	ordinal	boolean	-	2	0 = Absence 1 = Presence
salcut	Salvage cut	ordinal	boolean	-	2	0 = Absence 1 = Presence
clean	Clean	ordinal	boolean	-	2	0 = Absence 1 = Presence
sancut	Sanitation cut	ordinal	boolean	-	2	0 = Absence 1 = Presence
nother	Other type of neighbour management	ordinal	boolean	-	2	0 = Absence 1 = Presence
-	Management Index	cardinal	floating	-	2	-

Annex 3

Table 1: Summary table of procedures for circumference measurement implemented in special cases.

Special case	Procedure
Bifurcations or low branches	Only measure structures that separate from the main trunk at average distances of at least 130 cm from the ground.
Compartments connected to the main trunk	These compartments are included in the circumference measurement
Main structure divided into several separate compartments	Compartments are only taken into account if they result from the progressive disintegration of a single trunk.

Annex 4

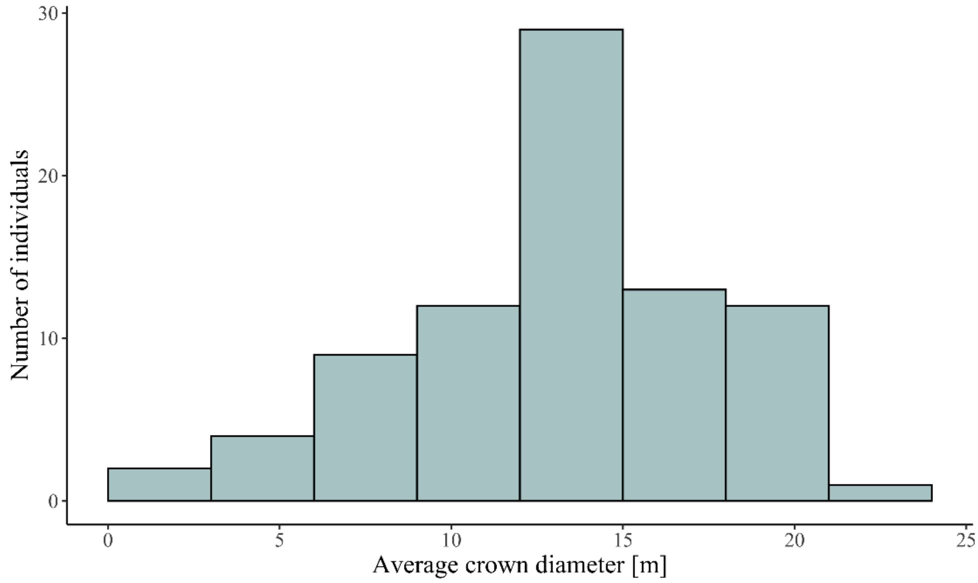

Figure 1: Number of individuals vs. average crown diameter (*da*). On the x-axis the average crown diameter (*da*) expressed in meters while on the y-axis the number of inventoried trees.

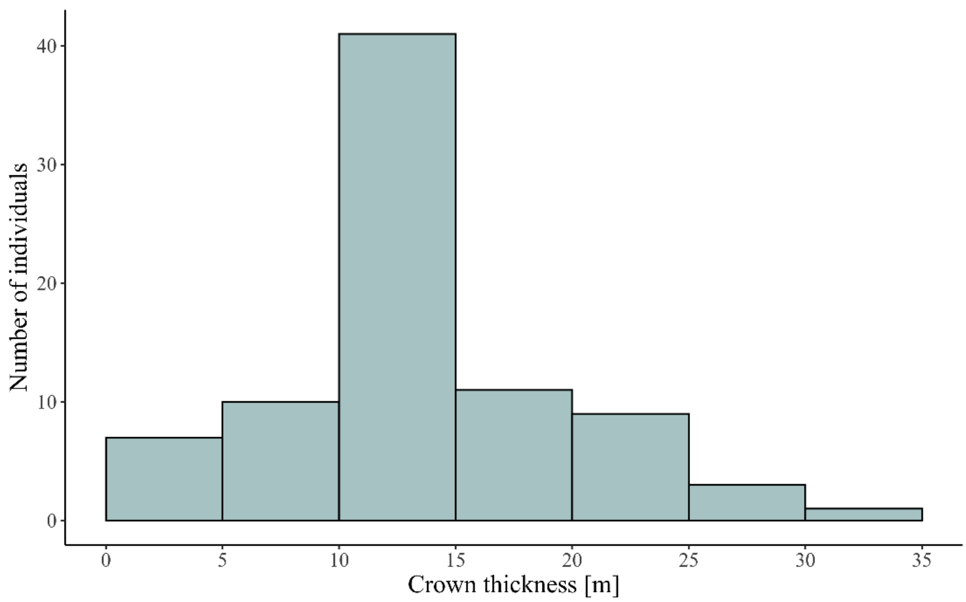

Figure 2: Number of individuals vs. Crown thickness (*cth2*). On the x-axis the Crown thickness expressed in meters while on the y-axis the number of inventoried trees. Crown thickness was calculated by subtracting Trunk height (*htrunk*) from Tree height (*htree*).

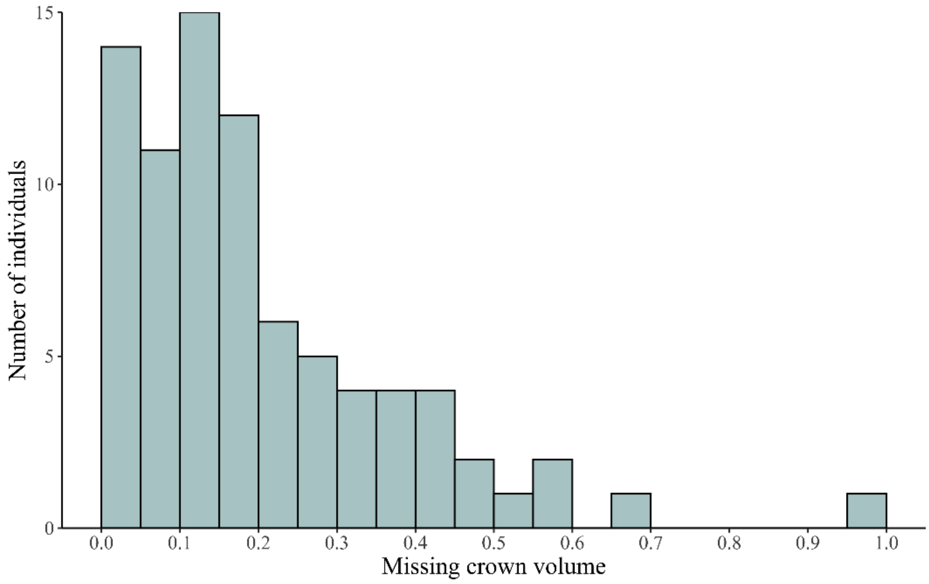

Figure 3: Number of individuals vs. Missing crown volume value (*vm2*). On the x-axis the Missing crown volume (expressed as the missing portion, with values from 0 to 1) while on the y-axis the number of inventoried trees.

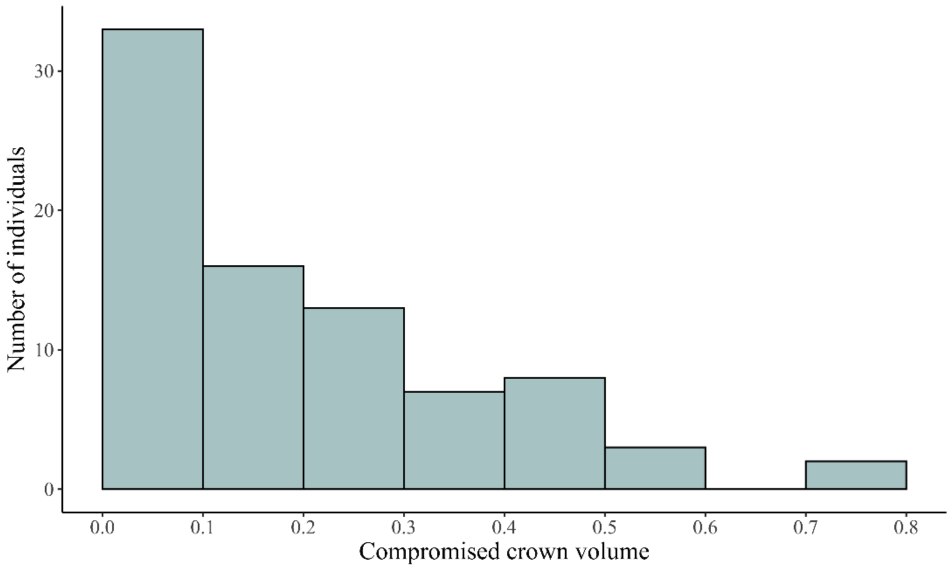

Figure 4: Number of individuals vs. Compromised crown volume (*vc2*). On the x-axis the Compromised crown volume (expressed as the compromised portion, with values from 0 to 1) while on the y-axis the number of inventoried trees.

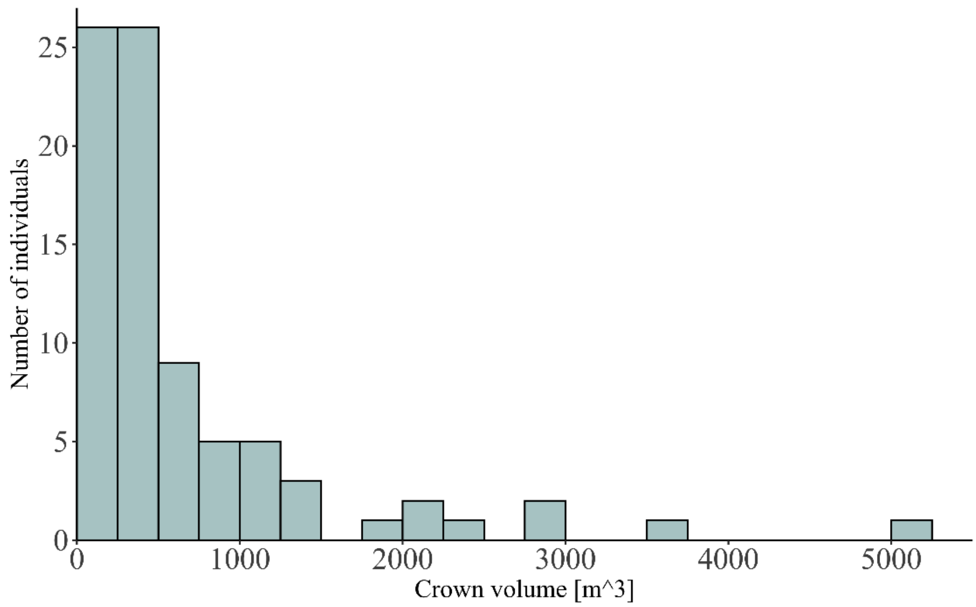

Figure 5: Number of individuals vs. crown volume (*vcrow*). On the x-axis the Crown volume (expressed in cubic meters) while on the y-axis the number of inventoried trees.

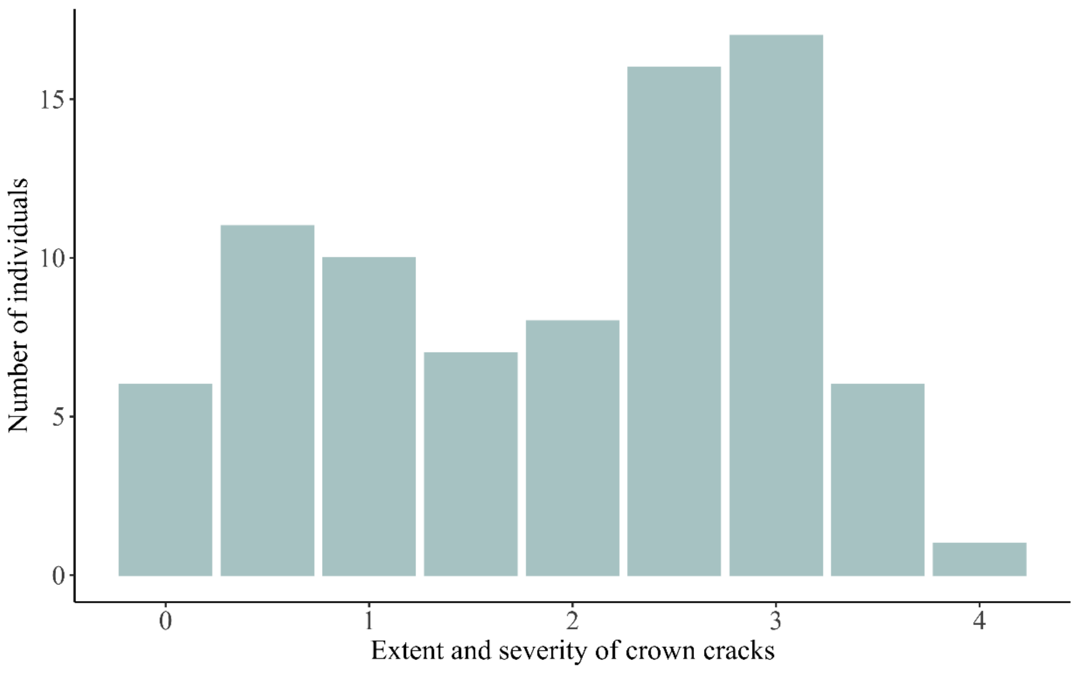

Figure 6: Number of individuals vs. extent and severity of crown cracks (*cc2*). On the x-axis the extent and severity of crown crack (0 = no visible cracks in the crown structure, 1 = few, minor cracks on the crown structure, 2 = some areas of the crown structure are characterized by not too severe cracks, 3 = severe cracks on one or more portions of the crown structure, 4 = severe cracks on the entire crown structure) while on the y-axis the number of inventoried trees.

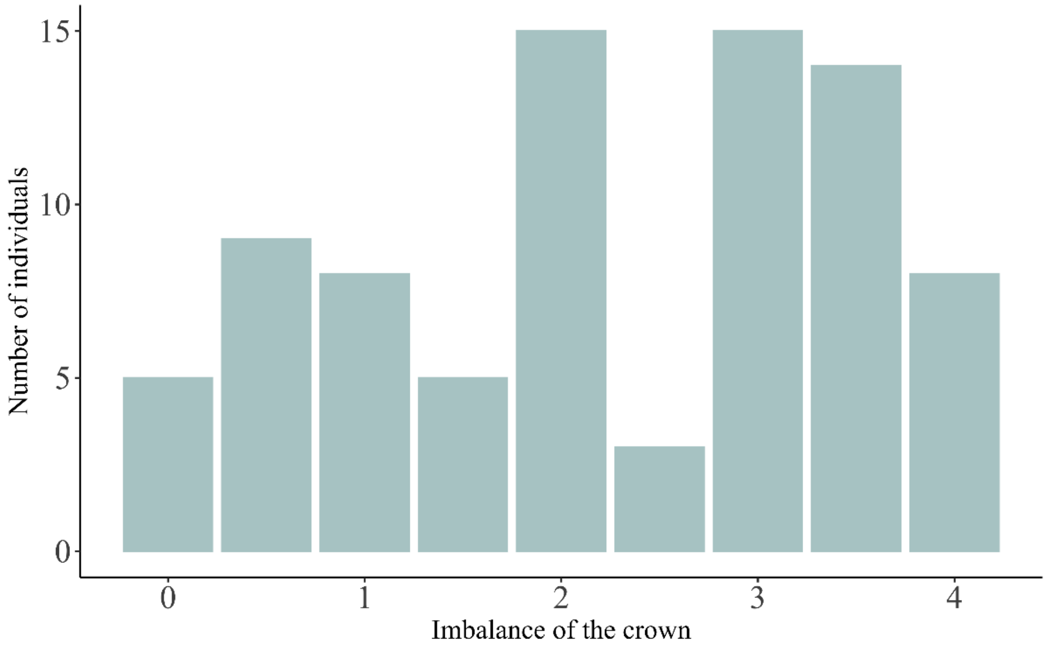

Figure 7: Number of individuals inventoried vs. imbalance of the crown (*cimb2*). On the x-axis the imbalance of the crown (0 = stable, well-distributed and balanced crown, 1 = between stable and slightly unstable crown unevenly distributed in space, 2 = slightly unstable and unevenly distributed crown, 3 = clear structural imbalance of the crown that could compromise the structure stability of the tree, 4 = strong structural imbalance in the crown with branches not uniform distributed and ramifications too extensive to guarantee plant stability) while on the y-axis the number of inventoried trees.

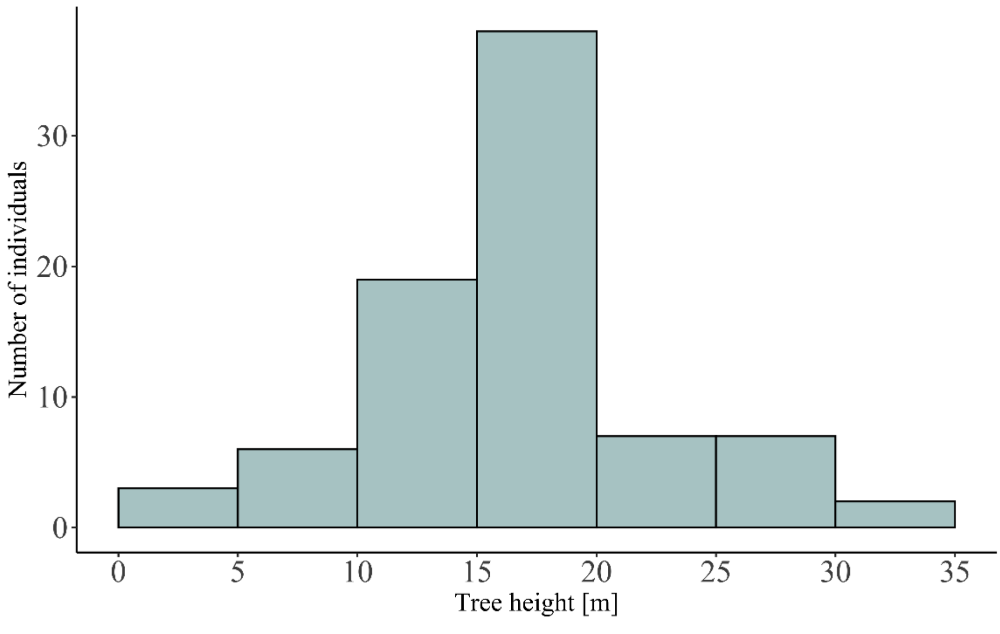

Figure 8: Number of individuals vs. tree height (*htree2*). On the x-axis the tree height (expressed in meters) while on the y-axis the number of inventoried trees.

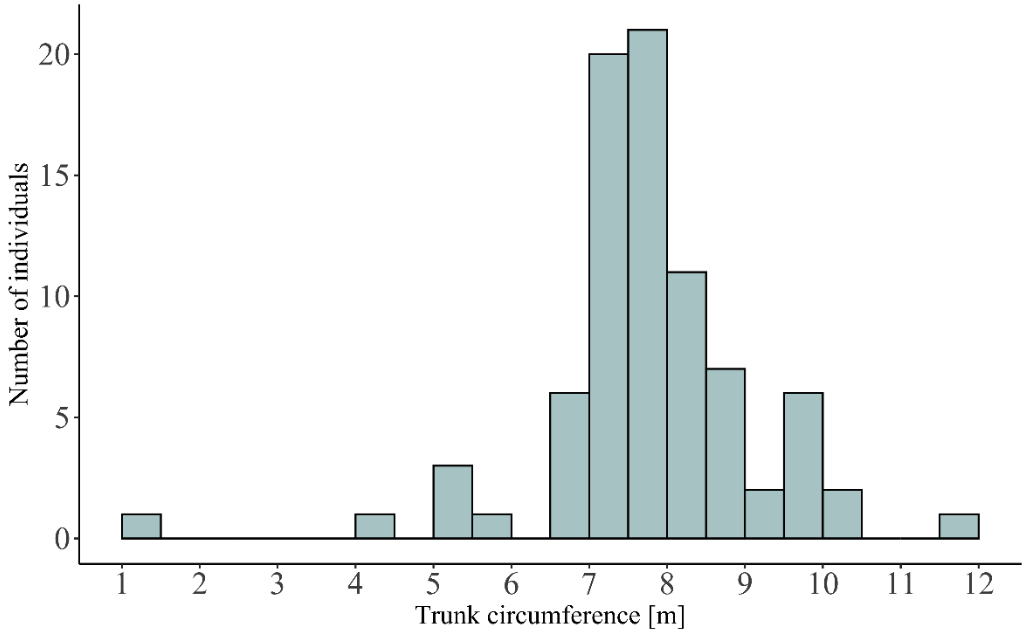

Figure 9: Number of individuals vs. trunk circumference (*cir*). On the x-axis the trunk circumference (expressed in meters) while on the y-axis the number of inventoried trees.

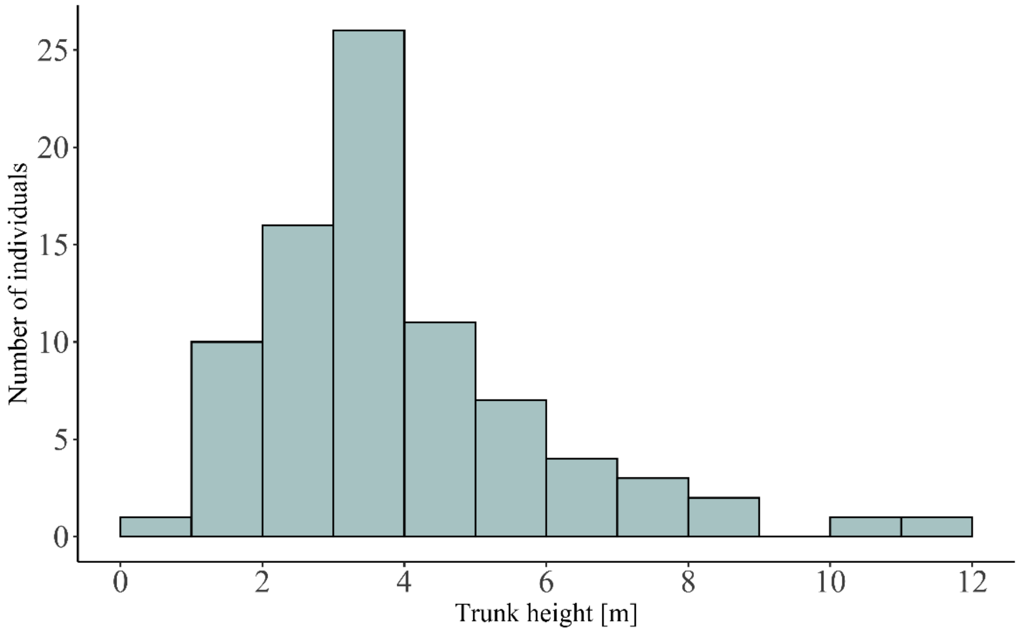

Figure 10: Number of individuals vs. trunk height (*htrunk*). On the x-axis the trunk height (expressed in meters) while on the y-axis the number of inventoried trees.

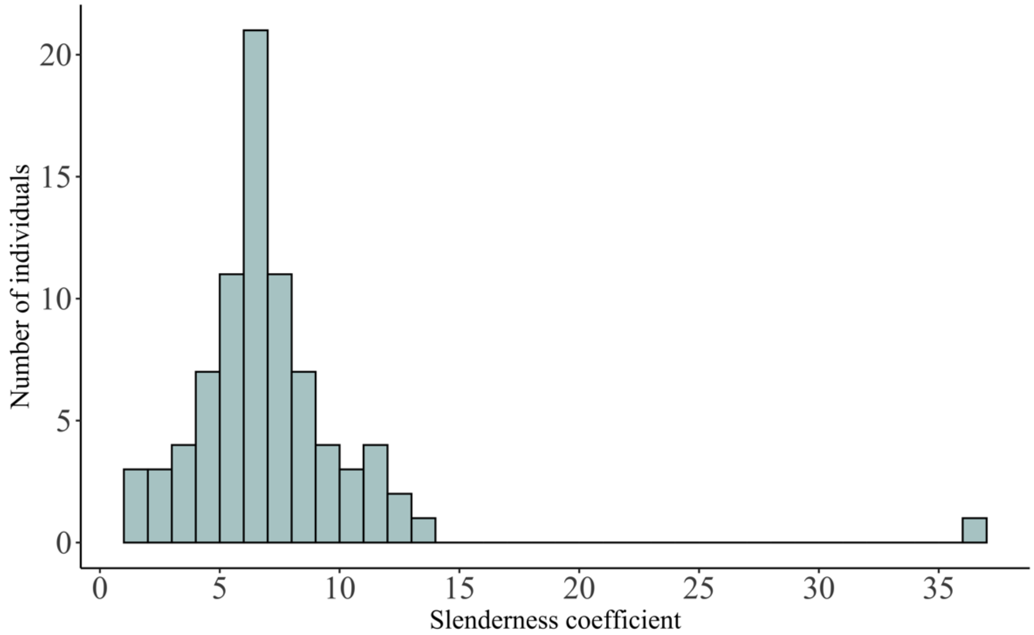

Figure 11: Number of individuals vs. slenderness coefficient (*slender*). On the x-axis the slenderness coefficient values while on the y-axis the number of inventoried trees.

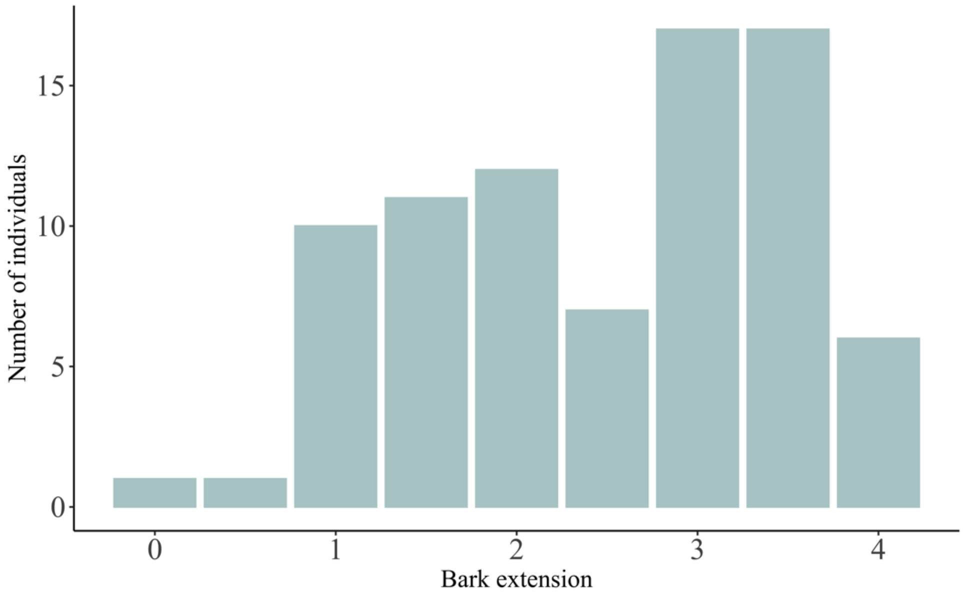

Figure 12: Number of individuals inventoried vs. bark extension (*barex2*). On the x-axis the degree of bark extension (0 = completely debarked trunk, 1 = bark cover ¼ of the circumference of the trunk, 2 = bark cover ½ of the circumference of the trunk, 3 = bark cover ¾ of the circumference of the trunk, 4 = bark cover the full circumference of the trunk) while on the y-axis the number of inventoried trees.

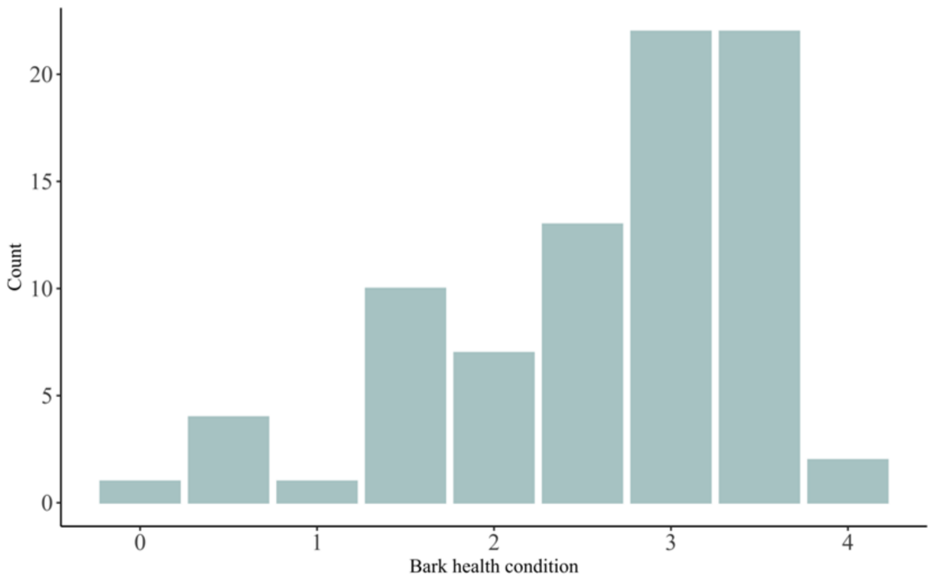

Figure 13: Number of individuals inventoried vs. bark health condition (*barco2*). On the x-axis the bark health condition (0 = very weak bark with functionality not assured, 1 = tree bark with weakened and/or partly not intact functionality on most of the trunk, 2 = tree bark with some weakened or/and partly not intact functionality, 3 = firm and vital tree bark on most of the trunk with only a few signs of weakening, 4 = firm and vital bark with clear signs of full functionality bark cover the full circumference of the trunk) while on the y-axis the number of inventoried trees.

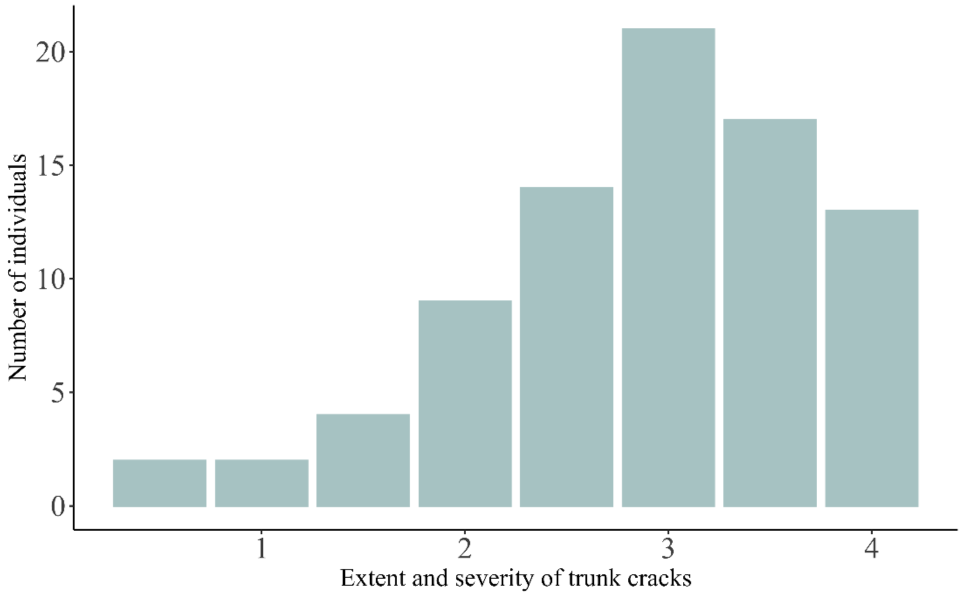

Figure 14: Number of individuals inventoried vs. extent and severity of trunk cracks (*tc2*). On the x-axis the extent and severity of trunk cracks (0 = apparently no cracks on the inferior part of the trunk structure, 1 = few, minor cracks on the inferior trunk structure, 2 = some areas of the inferior trunk structure are characterized by not too severe cracks, 3 = severe cracks on one or more portions of the inferior trunk structure, 4 = severe cracks present on the entire inferior trunk structure) while on the y-axis the number of inventoried trees.

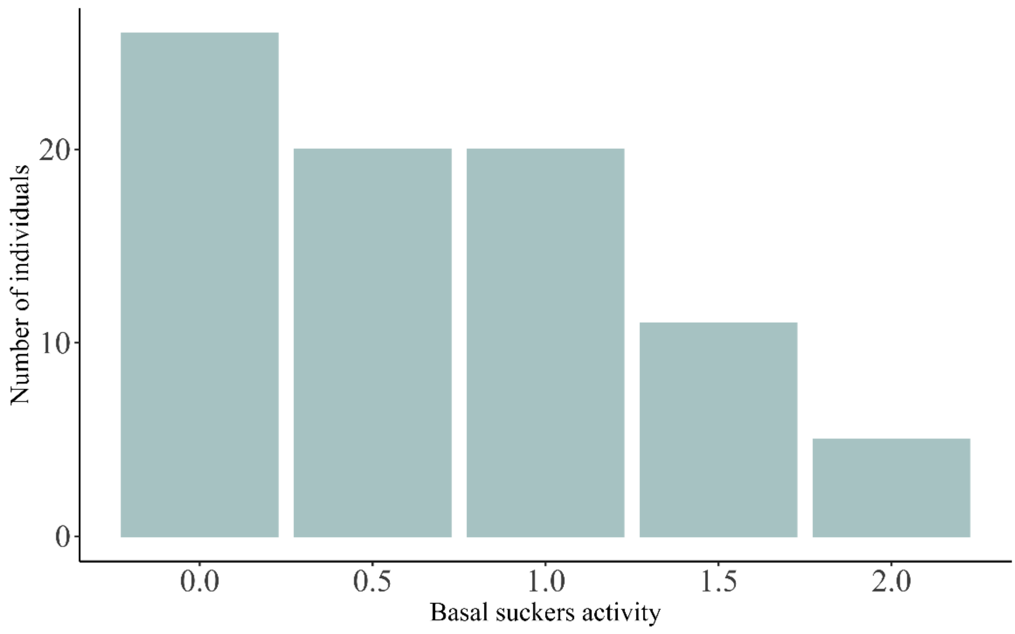

Figure 15: Number of individuals inventoried vs. basal suckers activity (*bact2*). On the x-axis the values of the basal suckers activity (0 = no activity/proliferation, 1 = moderate activity/ proliferation, 2 = important activity/ proliferation) while on the y-axis the number of inventoried trees.

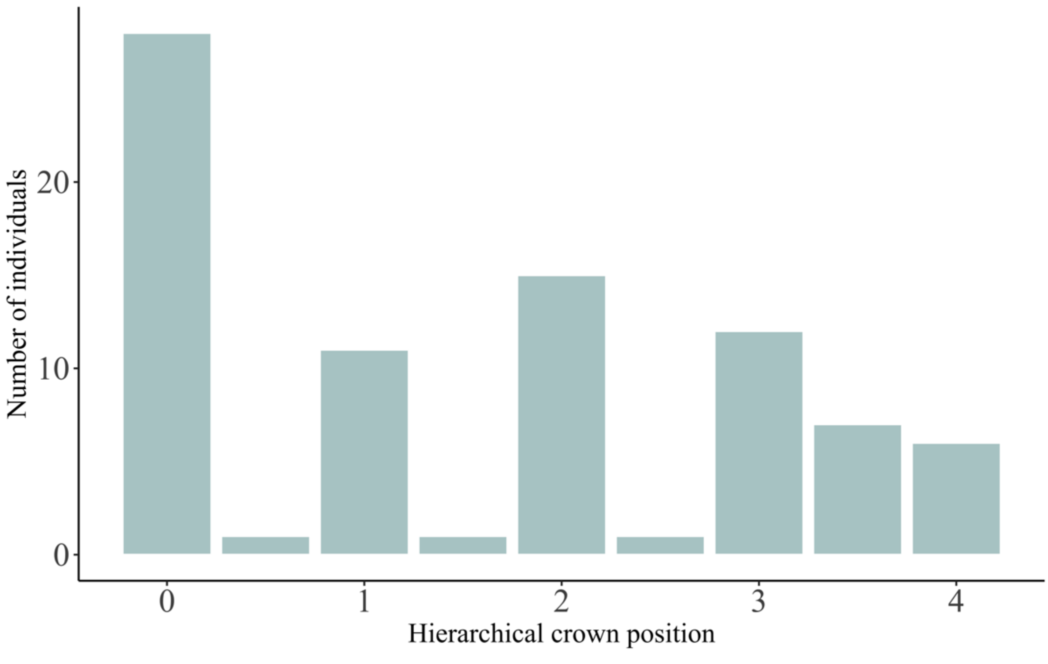

Figure 16: Number of individuals inventoried vs. hierarchical crown position (*cpos2*). On the x-axis the values of the hierarchical crown position (0 = open grow, 1 = dominant crown, 2 = co-dominant crown, 3 = intermediate crown, 4 = supressed crown) while on the y-axis the number of inventoried trees.

Annex 5

Figure 1: Tree ID78, with the collapsed trunk (left picture) and the twig (right picture).

Annex 6

Table 1: Distribution of competitors by species and by cardinal sector.

Spec	N	NE	NW	E	W	S	SE	SW
Aa	1	1	0	0	0	1	0	0
Ag	4	3	1	4	1	2	7	1
Ai	0	0	0	0	0	0	0	1
Bp	6	7	7	7	6	3	4	5
Ca	12	21	16	15	11	10	12	10
Cs	8	12	16	16	15	20	17	15
Fe	1	1	1	1	4	2	0	3
Pa	10	3	5	4	8	3	5	3
Jr	0	0	1	0	0	1	0	1
Fs	3	2	0	2	0	1	1	1
Pav	0	0	0	1	0	0	0	0
Qp	0	1	0	0	0	0	2	0
la	1	0	0	0	0	0	0	0
Ps	1	0	0	0	0	0	0	0
Tp	2	2	0	2	4	1	2	2
XX	1	2	2	0	0	1	1	1
Ld	0	0	0	0	0	1	0	0
Sa	0	0	0	0	0	0	0	1
To	0	1	0	0	0	0	0	0

Table 2: Minimum, mean and maximum distance of competitors by cardinal sector.

functions	distN	distNE	distE	distSE	distS	distSW	distW	distNW
max	14.70	14.80	15.00	15.00	15.00	15.00	13.90	14.10
mean	6.52	7.32	6.65	6.96	7.83	7.33	7.56	6.93
min	0.10	1.90	0.40	1.70	1.90	2.10	1.60	1.50

Table 3: Average distance of the 4 most frequent competitor species.

Species	Mean(distX)
Cs	8.23
Ca	8.10
Bp	5.69
Pa	5.89

Annex 7

Table 1: Minimum, 1st quantile, median, mean, 3rd quantile and maximum of the Health Index for each class of *all2*. The most remarkable aspect concerns the first row (in red) of the table, i.e. the distribution of the health index values for the 0.5 value of the all2 attribute. The variability with respect to the rest of the all2 scale is considerable. It ranges from a score of 0.25 (lowest) to 1.93 (highest).

all2	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
0.5	0.25	0.71825	0.9045	0.996682	1.262	1.935
1	0.4	1.09125	1.277	1.245313	1.455	1.905
1.5	0.884	1.367	1.476	1.546	1.7355	2.375
2	1.051	1.48075	1.7255	1.654429	1.878	2.055
2.5	1.593	1.698	1.791	1.908571	1.933	2.714
3	0.014	1.8135	1.882	1.673571	1.928	2.336
3.5	2.124	2.124	2.124	2.124	2.124	2.124

Table 2: Information regarding the monumental trees belonging to the 0.5 category of *all2* with considerable anomalous values (in red) for the health index.

ID	all2	health index	compTot	cir2	vcrow	cc2	barex2	barco2	cav2	tc2
94	0.5	1.77	0.98	9.8	740.73	3.5	3.5	3	**4**	3.5
98	0.5	1.93	0.84	4.44	305.88	0.5	4	3.5	**4**	0.5
132	0.5	1.54	0.59	8.31	207.35	2.5	3	3	**4**	1.5

Annex 8

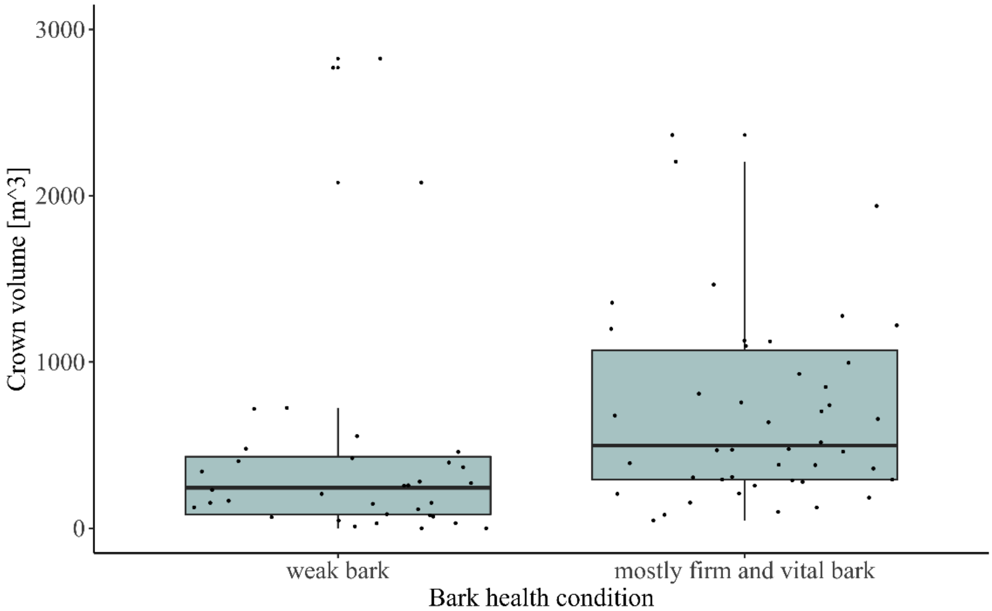

Figure 1: Crown volume (*vcrow*) vs. bark health condition (*barco2*). On the x-axis is the Bark health condition divided into two classes: weak bark (*barco2* < 2.5) and mostly firm and vital bark (*barco2* >= 3). On the y-axis, on the other hand, is crown volume (*vcrow*) expressed in cubic meters.

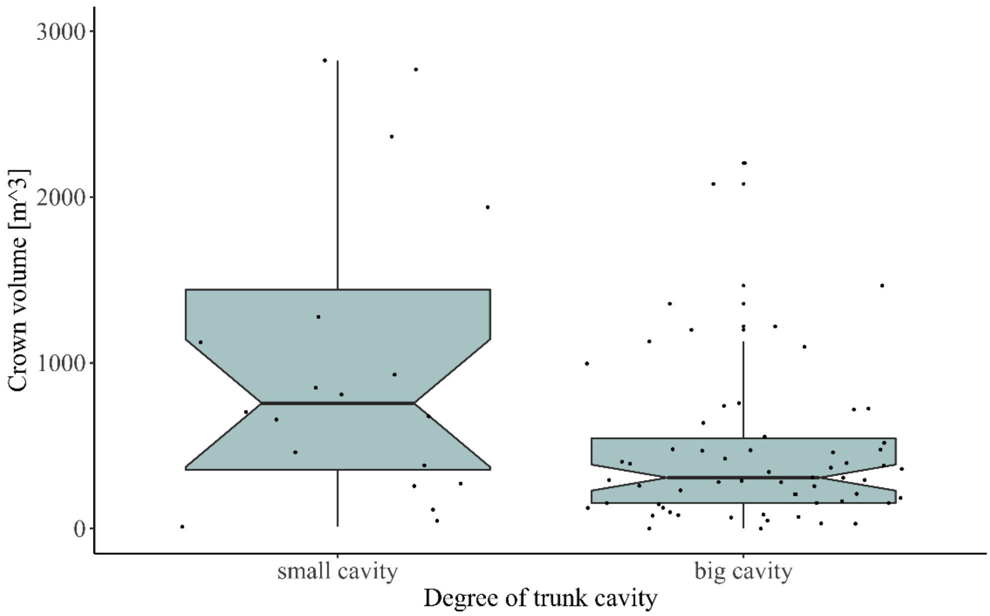

Figure 2: Crown volume (*vcrow*) vs. degree of trunk cavity (*cav2*). On the x-axis is the Degree of trunk cavity divided into two classes: small cavity (*cav2* <=2) and mostly firm and vital bark (*cav2* >= 2.5). On the y-axis, on the other hand, is crown volume (*vcrow*) expressed in cubic meters.

Annex 9

Table 1: Estimate and p-values of the linear regression between the general health (*all2*) and selected indexs/attributes.

Index/Attribute	Estimate	p-value
Health index	0.9128	3.07×10^{-8}
Competition index	-0.3837	5.06×10^{-3}
Stability index	0.2902	0.0579
Management index	0.06031	0.0929
barex2	0.44385	2.78×10^{-7}
cav2	-0.39868	6.31×10^{-7}
htree2	0.06260	4.2×10^{-5}
cth2	0.05896	6.5×10^{-5}
barco2	0.3925	6.6×10^{-5}
da	0.07689	1.07×10^{-4}
tc2	-0.3777	3.96×10^{-4}
vcrow	0.0003645	4.89×10^{-4}
cimb2	-0.1736	0.0199

Table 2: Estimate and p-values of the linear regression between the health index and selected indexs/attributes.

Index/Attribute	Estimate	p-value
Competition index	-0.15564	0.0705
Stability index	0.11663	0.222
Management index	0.01424	0.525
all2	0.35051	3.07×10^{-8}
htree2	0.049400	6.08×10^{-8}
tc2	-0.3212	4.25×10^{-7}
cav2	-0.17701	6.02×10^{-4}
cir2	0.06885	0.0988

Table 3: Estimate and p-values of the linear regression between the competition index and selected indexs/attributes.

Index/Attribute	**Estimate**	**p-value**
Health index	-0.2591	0.0705
Stability index	-0.4927	2.60×10^{-5}
Management index	-0.07919	5.06×10^{-3}
cclo2	0.28464	8.78×10^{-10}
cpos2	0.27928	4.54×10^{-9}
vc	1.4891	1.52×10^{-4}
cimb2	0.20597	4.17×10^{-4}
cc2	0.19084	4.018×10^{-3}
all2	-0.24527	5.06×10^{-3}
tc2	0.19641	0.0243
barex2	-0.1590	0.0312

Table 4: Estimate and p-values of the linear regression between the stability index and selected indexs/attributes.

Index/Attribute	**Estimate**	**p-value**
Health index	0.1596	0.222
Competition index	-0.40491	2.6×10^{-5}
Management index	0.12808	1.03×10^{-7}
cav2	-0.19351	1.42×10^{-3}
htree2	-0.03365	3.03×10^{-3}
da	-0.03958	7.22×10^{-3}
bact2	-0.23557	0.0303
htrunk2	0.07036	0.0333
vm	-0.7834	0.0389
hcb2	0.1054	0.0464
all2	0.15245	0.0579

Annex 10

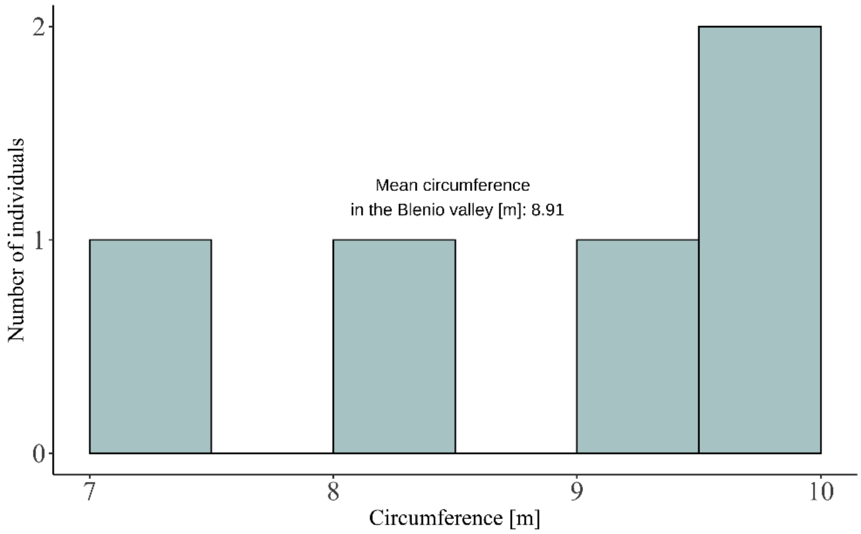

Figure 1: Distribution of inventoried individuals in the Blenio Valley according to Trunk circumference at breast height *(cir)* classes. On the x-axis are the circumference classes while on the y-axis is the number of individuals inventoried.

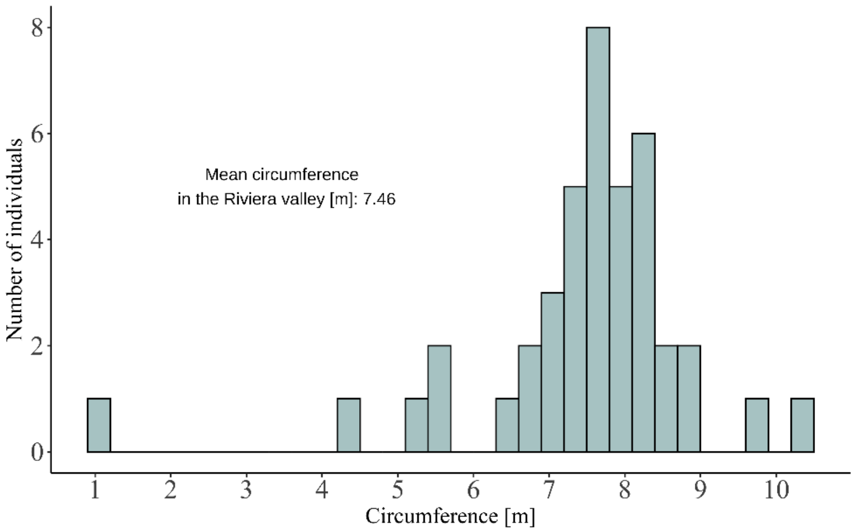

Figure 2: Distribution of inventoried individuals in the Riviera Valley according to Trunk circumference at breast height *(cir)* classes. On the x-axis are the circumference classes while on the y-axis is the number of individuals inventoried.

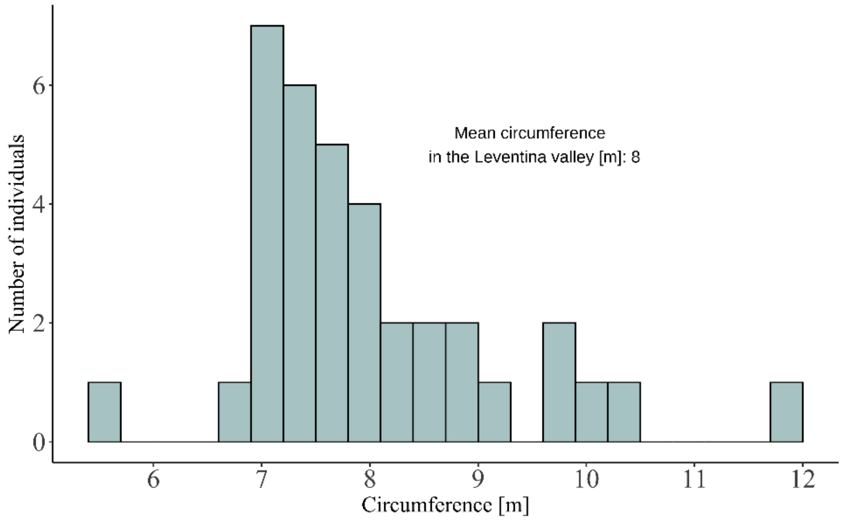

Figure 3: Distribution of inventoried individuals in the Leventina Valley according to Trunk circumference at breast height *(cir)* classes. On the x-axis are the circumference classes while on the y-axis is the number of individuals inventoried.

Annex 11

Table 1: Estimate and p-values of the linear regression between the general health attribute (*all2*) and selected geographical and environmental attributes.

Attribute	Estimate	p-value
for20r100	-2.532×10^{-5}	0.0375
slo25	-0.019447	0.0523

Table 2: Estimate and p-values of the linear regression between the stability index and selected geographical and environmental attributes.

Attribute	Estimate	p-value
herb1	0.32522	3.58×10^{-8}
herb2	0.29155	3.92×10^{-8}
for20r20	-6.26×10^{-4}	4.74×10^{-7}
for20r50	-1.12×10^{-4}	4.61×10^{-6}
for00r50	-1.05×10^{-4}	8.64×10^{-5}
bu50	1.33×10^{-3}	2.43×10^{-3}
bu100	3.831×10^{-4}	3.70×10^{-3}
rock2	-0.2690	0.0116
slo20	-0.016118	0.0240
dpath20	-1.41×10^{-3}	0.0848
alt	7.68×10^{-4}	0.0877
droad20	-6.15×10^{-4}	0.0935

Table 3: Estimate and p-values of the linear regression between the competition index and selected geographical and environmental attributes.

Attribute	Estimate	p-value
For20r20	6.51×10^{-4}	2.59×10^{-6}
For20r50	1.14×10^{-4}	2.94×10^{-5}
For20r100	3.491×10^{-5}	2.23×10^{-4}
Herb2	-0.19403	0.00183
N40	-0.42622	0.00341
N10	-0.38056	0.00613
Bu50	-0.0013192	0.00657
Bu100	-0.003717	0.0112

Annex 12

Table 1: Table summarising the geographical location (attributes: *valley*, *mun*, *loc* and *alt*) of the 19 dead monumental chestnut trees, their general health status (*all1*) in the first inventory and the presumed main cause of death (*dEx*).

ID	Valley	Municipality	Locality	Altitude	General health condition (*all1*)	Death explanation
23	Leventina	Rossura	Fontanè	1000	0.5	environmental
28	Leventina	Personico	Quattro Gambe	940	1	environmental
40	Leventina	Bodio	Bitanengo	883	2	human
55	Riviera	Osogna	Pönt	739	0.5	environmental + human
88	Riviera	Claro	Donadino	813	0.5	environmental + human
89	Riviera	Claro	Ramigòi	735	1	environmental
95	Riviera	Iragna	Citt	742	1	human
100	Riviera	Iragna	Citt	704	1.5	environmental + human
127	Riviera	Lodrino	Sacco	663	2.5	environmental
139	Leventina	Giornico	Catto	643	1.5	environmental
159	Riviera	Iragna	Ponte	867	1	environmental
203	Leventina	Giornico	Magianengo	782	2	environmental
210	Riviera	Lodrino	Sacco	640	1	environmental
215	Riviera	Cresciano	Bàssera	939	2	environmental
217	Leventina	Bodio	Bidesco	954	2	environmental
218	Leventina	Bodio	Bidesco	963	1.5	environmental
237	Riviera	Preonzo	Cher	760	1.5	environmental
248	Leventina	Chironico	Grumo	823	1	human
269	Riviera	Claro	Moncrino	787	2	environmental + human

Annex 13

Tree ID23

Field notes: "The ID23 monumental tree is found crashed to the ground. It can be deduced from the vegetation around it and on the remaining trunk that it has been there for many years already. The surrounding vegetation is mainly characterised by hazelnut and blackberry bushes. The cause of death is impossible to establish; but already in the first inventory the health condition of the monumental chestnut tree was low (*all1*= 0.5). A possible cause of death could have been the fall of the supporting structure, but it is not possible to determine the exact cause. From the before and after photographs below one can immediately see the change in the degree of management around the monumental tree. The area now looks abandoned."

Figure 1: Standing tree ID23 on the left (2004), crashed tree on the right (2021)

Tree ID28

<u>Field notes</u>: “The chestnut tree is found crashed to the ground and is on the date of the survey largely covered by snow. The geographic location (latitude and longitude), a recognisable segment of the facade and the absence of chestnut trees with a considerable diameter within a radius of 50 m confirm its identity: it is the chestnut tree ID28. It can immediately be noticed that many other trees in the vicinity have fallen to the ground just like ID28, which leads to the assumption that the cause of death of this chestnut tree is due to natural causes. Already during the first inventory a certain instability tree was noted.The terrain is landslide-prone and has many rocks, some of which are large in size. The snow blanket that now covers the landscape makes it difficult to carry out the survey. The chestnut tree is located in the Personico chestnut grove, as indicated by a wooden sign at the beginning of the path near the "Lago della val d'Ambra". This chestnut grove is indicated by the Patriziato of Personico as one of the most extensive in Ticino, in fact it comprises 110 hectares occupied by chestnut trees of which 12 are indicated as monumental (Patriziato di Personico). The definition used by the Patriziato of Personico to define a monumental chestnut is not indicated on their official website, but in the municipality of Personico 11 specimens have been surveyed in this research, two, ID29 and ID291 in the locality of Ramlitt, along the same path leading to individual ID28.”

Figure 2: Status of the tree ID28 in 2003 (on the left) compared with that of 2021(on the right)

Tree ID40

Field notes: "The tree in question is located in a private area partly on a stone wall. A fairly busy road linking Bidesco and Bodengo runs just below it. The tree no longer has a crown and has no live shoots on either the collar or the trunk, nor on the remaining parts. It is assumed that the death of this specimen was due to human hands. The reasons for this action are unknown and even various interviews with local people have not clarified the circumstances. The crown was already very small during the first inventory and the tree had no dangerous branches. Perhaps too severe pruning of the crown led to the tree's death, but without an interview with the owner of the land the fatality remains unknown."

Figure 3: Status of the tree ID40 in 2003 (on the left) compared with that of 2021 (on the right)

Tree ID55

Field notes: "Testimonies collected in the field identify this specimen as the monumental tree per excellence, despite its death it enthrones the surrounding land and bears witness to a vanished culture. One particular witness recalls a day (ten years ago) of strong winds that caused a large crack in the tree's trunk. To prevent a collapse, the authorities reduced the crown to a minimum, but the severe pruning led slowly to its death."

Figure 4: Status of the tree ID55 in 2003 (on the left) compared with that of 2021(on the right)

Tree ID88

Figure 5: Status of the tree ID88 in 2002 (on the top) compared with that of 2021(on the bottom)

Tree ID89

Field notes: "The tree is still standing in the middle of the forest. It is completely debarked and there are no signs of human intervention. A birch tree about 3 m high can be seen on the crown, which could indicate the tree's rather recent death, but this is only a speculation. Krebs mentioned an unidentified disease in his inventory notes, which seems to have taken hold of the tree and probably led to its death."

Figure 6: Status of the tree ID89 in 2004 (on the left) compared with that of 2021 (on the right)

Tree ID95

Field notes: "The tree has been cut down and removed, only the base of the trunk remains visible on the ground. It was probably a dangerous plant that threatened the stone built hut above the tree. Many birch trees have grown around and into the hollow of the remaining trunk. Their size and number indicate that the monumental tree was removed a long time ago."

Figure 7: Status of the tree ID95 in 2002 (on the left) compared with that of 2021(on the right)

Tree ID100

<u>Field notes</u>: The monumental tree was cut and the derived wood completely removed. Several blackberries have grown inside what remains of the trunk. Oral sources report that the cutting took place around 2010; after a strong wind and the collapse of part of the trunk. In order to avoid accidents with the goats and farmers who are often in the vicinity, it was decided to dismantle it.

Figure 8: Status of the tree ID100 in 2004 (on the left) compared with that of 2021(on the right)

Tree ID127

Field notes: A farmer with a nearby house reported that the tree fell due to natural causes a long time ago. Today it is used as shelter for cattle (perhaps donkeys) on sunny days. Some birch trees now growing on the trunk of the dead monumental tree confirm the date of death to a long time ago. The trunk, however, shows cuts made with a saw on some parts, probably dating back to after its collapse.

Figure 9: Standing tree ID127 on the left (2002), crashed tree on the right (2021)

Tree ID139

Field notes: "The tree is located in a fairly enclosed forest, there is a dry stone wall next to the tree and it lies in a terraced area. The tree has collapsed to the ground. The ground all around is wet, perhaps this feature favoured the uprooting. The cause of death is most likely due to natural causes"

Figure 10: Standing tree ID139 on the left (2004), crashed tree on the right (2021)

Tree ID159

Field notes: “The tree is located just below a (managed) meadow that is part of a mount with several small buildings still in use. The area around the chestnut tree has many crashed trees on the ground that may have died due to a common occurrence. On the remaining trunk there are no signs of human intervention, indicating that the cause of death is most likely natural. It could be assumed that an exceptional event (perhaps strong wind, storm) destabilized the structure of the tree and that it consequently collapsed, along with many trees around it.”

Figure 11: Standing tree ID159 on the left (2002), crashed tree on the right (2021)

Tree ID203

<u>Field notes</u>: "The chestnut tree is found in the vicinity of some mountain houses that are probably disused or rarely visited. The specimen is crashed to the ground and several birch trees grow on it, some with a diameter greater than 12 cm, indicating a collapse that occurred many years ago. Death is most likely due to natural factors, as there are no indications to suggest otherwise."

Figure 12: Standing tree ID203 on the left (2004), crashed tree on the right (2021)

Tree ID210

Field notes: "The tree is located just below a dry stone wall that borders a small clearing where a donkey fence is located. There are no visible signs of human intervention on the crashed trunk. Just above the roots there is a very extensive rot that may have affected the (most probably natural) mortality event. Many other chestnut trees in the vicinity are crashed to the ground, perhaps they all fell due to strong winds."

Figure 13: Standing tree ID210 on the left (2003), crashed tree on the right (2021)

Tree ID215

Field notes: "The tree is located in the municipality of Cresciano in a fairly sparse forest just below the line of a path. The chestnut tree was growing on a large rock and is now lying on the ground in the downstream area, having fallen from a small cliff. It can be seen that the roots of the specimen are very small, due to the substrate on which it grew, which did not allow for a greater depth. This feature probably contributed to the tree's crashing, perhaps due to strong winds or land slide."

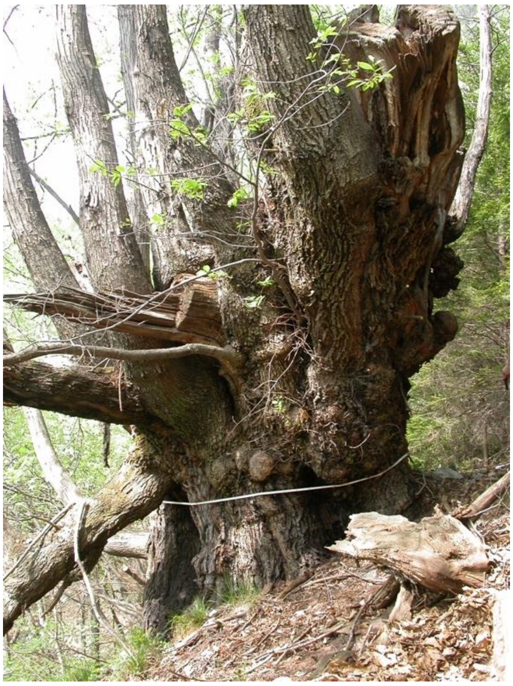

Figure 14: Standing tree ID215 on the left (2003), crashed tree on the right (2021)

Tree ID217

Field notes: "What remains of this monumental tree is located in Bidesco in the municipality of Bodio. The trunk has no visible (man-made) cuts. The fall did not uproot the root system, it seems that there was a collapse near the collar. The death probably occurred a long time ago, the vegetation around the crashed trunk is in fact very lush and there is a chestnut tree (about 3 m high) growing in the middle of the trunk of the analysed specimen. In the area some trees have been cut down, the reason remains unknown."

Figure 15: Standing tree ID217 on the left (2003), crashed tree on the right (2021)

Tree ID218

<u>Field notes:</u> "The tree is located in a forest characterised by chestnut, fir and beech trees. The trunk of the tree lies crashed to the ground without bark, the root system was not uprooted during the crash. The cause of death is probably due to natural causes, as there is no evidence to suggest otherwise. Above the trunk lying on the ground, the crowns of the trees surrounding it have completely closed the sky, perhaps indicating that the crown of the monumental chestnut tree in the past had a subordinate hierarchical position."

Figure 16: Standing tree ID218 on the left (2007), crashed tree on the right (2021)

Tree ID237

Field notes: "Not many metres away from the trunk that now lies crashed on the ground is an old abandoned charcoal pile, and a little further away an old ruin (Cassinetta). The tree now is found in the middle of a landslide, which most probably caused the death of the specimen. In fact, the tree seems to have slid downhill from its position 20 years ago, and many other trees in the vicinity seem to have suffered the same fate."

Figure 17: Standing tree ID237 on the left (2004), crashed tree on the right (2021)

Tree ID269

Field notes: "This individual, of which only the lower stump of the trunk remains, was cut and taken away. The tree was located next to a busy unpaved road and perhaps the reason for its removal was due to safety considerations. The clearing appears to go back a long time, as there are several small trees growing from the remaining stump. In the surrounding area other trees have been cut down or have collapsed."

Figure 18: Standing tree ID269 on the left (2004), crashed tree on the right (2021)

Annex 14

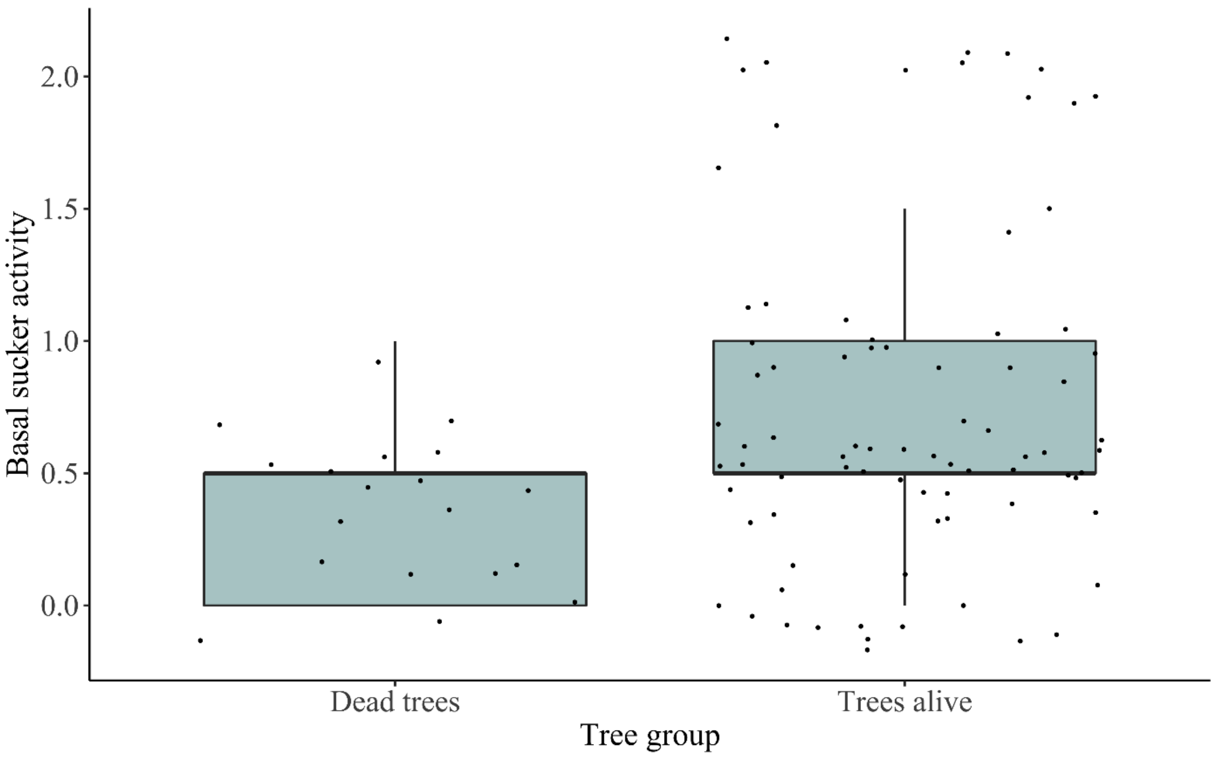

Figure 1: Distribution of inventoried dead and live trees according to basal sucker activity (*bact1*) during the first inventory. On the x-axis is the Tree group with the subdivision dead trees/alive trees. On the y-axis, on the other hand, the values of basal sucker activity (*bact1*).

Annex 15

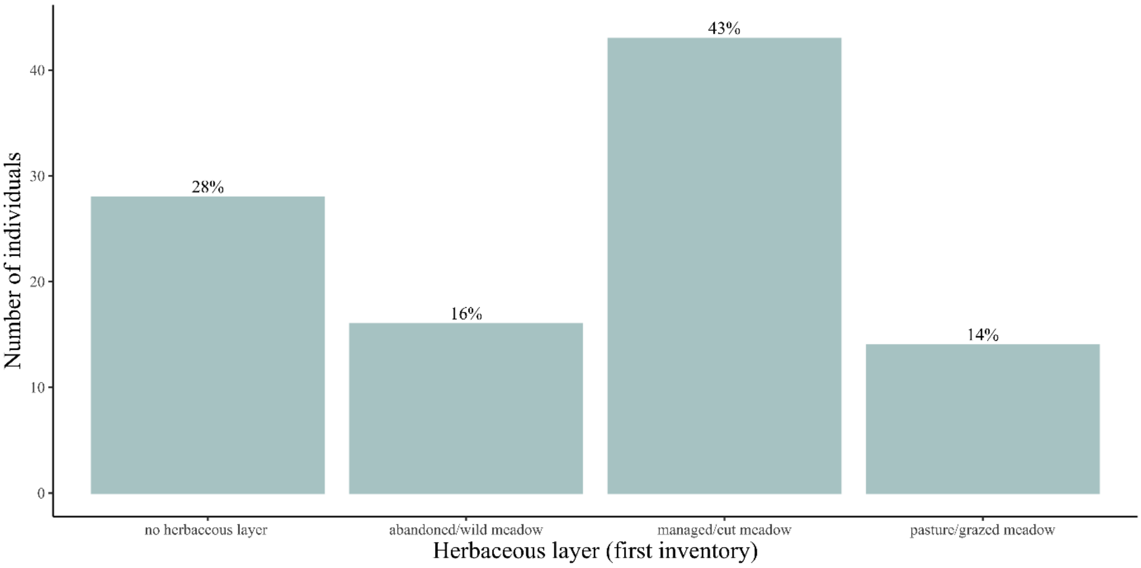

Figure 1: Distribution of inventoried trees according to the values of the herbaceous layer (*herb1*) attribute of the first inventory. On the x-axis are the values of the herbaceous layer (0 = No herbaceous layer, 1 = Abandoned/wild meadow, 2 = Managed/cut meadow, 3 = Pasture/grazed meadow) while on the y-axis is the number of inventoried trees.

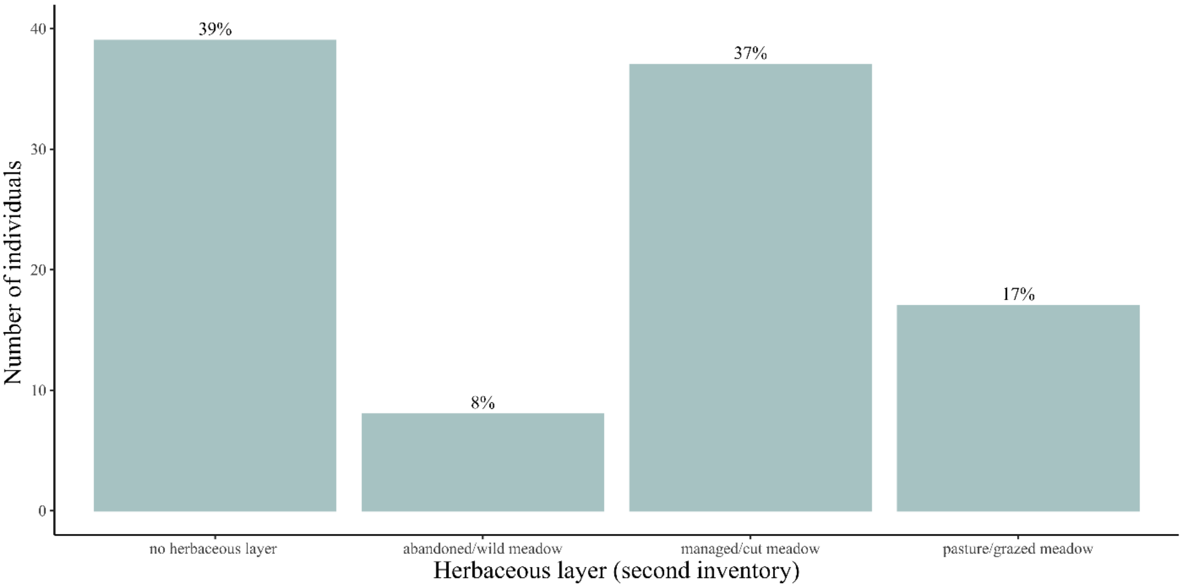

Figure 2: Distribution of inventoried trees according to the values of the herbaceous layer (*herb2*) attribute of the second inventory. On the x-axis are the values of the herbaceous layer (0 = No herbaceous layer, 1 = Abandoned/wild meadow, 2 = Managed/cut meadow, 3 = Pasture/grazed meadow) while on the y-axis is the number of inventoried trees.

Annex 16

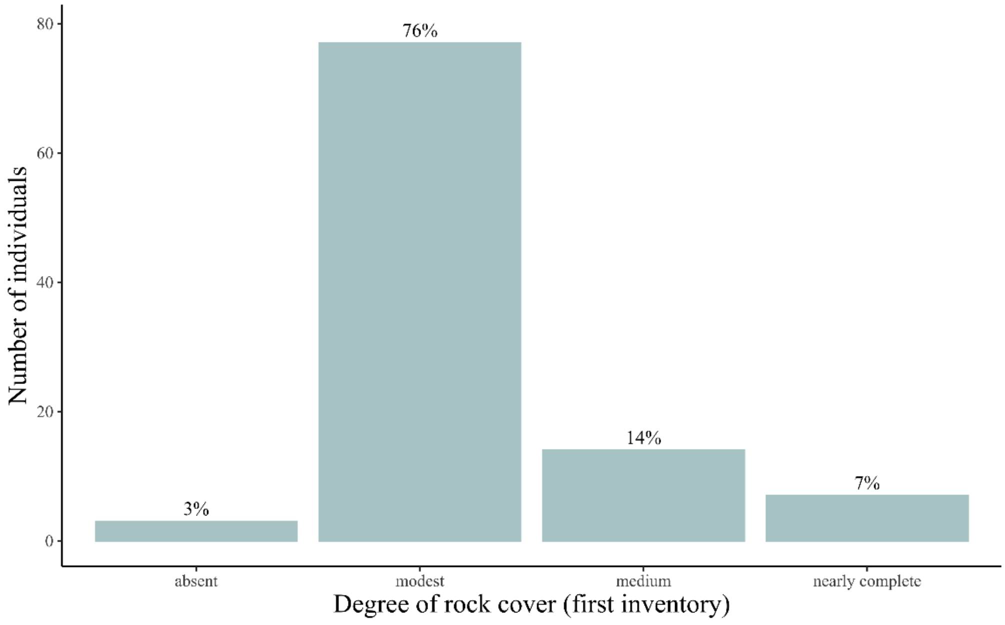

Figure 1: Distribution of inventoried trees according to the values of the degree of rock cover (*rock1*) attribute of the first inventory. On the x-axis are the values of the degree of rock cover (0 = absent, 1 = modest, 2 = medium, 3 = nearly complete) while on the y-axis is the number of inventoried trees.

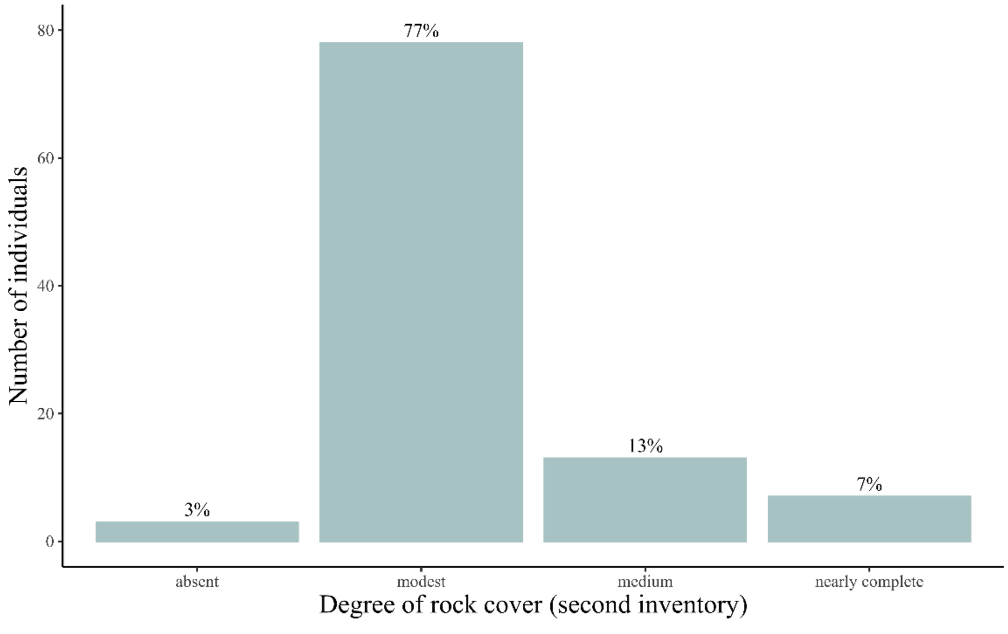

Figure 2: Distribution of inventoried trees according to the values of the degree of rock cover (*rock2*) attribute of the second inventory. On the x-axis are the values of the degree of rock cover (0 = absent, 1 = modest, 2 = medium, 3 = nearly complete) while on the y-axis is the number of inventoried trees.

Annex 17

Figure 1: Distribution of inventoried trees according to degree of selva management (*man1*) of the first inventory. On the x-axis we find the Degree of selva management values (0 = Abandoned selva, 1 = Minimal selva management, 2 = Managed restored selva) while on the y-axis we find the number of inventoried trees. At the top of each column also is the number of inventoried trees belonging to that degree of selva management class expressed as a percentage of the total.

Figure 2: Distribution of inventoried trees according to degree of selva management (*man2*) of the second inventory. On the x-axis we find the degree of selva management values (0 = Abandoned selva, 1 = Minimal selva management, 2 = Managed restored selva) while on the y-axis we find the number of inventoried trees. At the top of each column also is the number of inventoried trees belonging to that degree of selva management class expressed as a percentage of the total.

Annex 18

Figure 1: Trunk of the monumental trees ID43 located in the municipality of Chironico (on the left) and ID63 located in the municipality of Claro (on the right). Both individuals are characterised by a hollow trunk, although in the case of ID63 it is not possible to see the cavity that has spread from the centre towards the outside of the trunk. From the cavities, suckers can be observed.

Annex 19

Figure 1: Monumental chestnut tree ID247 located in the municipality of Chironico. In the photograph, it can be seen that the part to the right of the trunk is compromised. Looking carefully, one can see a fairly clear line (compartmentalisation of the deteriorated part) between the compromised part and the part that is still vital and vigorous. It can also be noticed how the crown above the compromised part is very small and also decaying.

Annex 20

Figure 1: Monumental chestnut tree ID238 located in the municipality of Personico, the tree inside is hollow and it is possible to walk through the trunk without much difficulty, going in on one side and out on the other. The tree is therefore divided in two in the aerial part of the trunk suggesting at least two semi-autonomous compartments, there is however no information on the root system, which is probably still shared. The inner cavity of the tree has bark in some parts suggesting effective and still ongoing healing.

Annex 21

Figure 1: Monumental chestnut ID133 located in the municipality of Iragna. The tree has lost almost a third of its total volume, but probably thanks to an earlier compartmentalisation process only the damaged part of the tree has fallen to the ground without compromising the specimen's life. The tree is now practically split in two, and these two parts are probably semi-independent, apart perhaps from the root system. The trunk section on the right has a very vigorous crown in contrast to the trunk section on the right.

Annex 22

Figure 1: Monumental tree ID134 located in the municipality of Iragna. One can see how the upper part of the crown is exhausted and dried out. An inner crown can still be distinguished between the trunk of the tree and the decayed part of the crown. A pruning intervention could reinvigorate the specimen with positive consequences.