



The Historical Garden Terra Nostra (São Miguel Island, Azores): The Contribution of Geographic Information System Tool to Content Development

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Abstract

*Placed in a landscape of great beauty, Terra Nostra Garden has more than two centuries of history, a unique landscape architecture, a dense canopy, several botanical collections, and thermal waters. The garden is located at Furnas village, an active volcanic area of the Azorean Island of São Miguel. The increased number of visitors associated with the Terra Nostra Garden Hotel and the garden natural SPA, triggered the need of a Geographic Information System (GIS) to improve both park management and contents communication. This work aimed to add scientific and economical value to the historical Terra Nostra Garden through the implementation of a GIS. With this purpose we established the following specific objectives: describe the origin and evolution of Terra Nostra Garden, supported on published work, unpublished notes, and age determination in georeferenced tree specimens; implement a GIS linked to walking trails covering the maximum points of interest regarding: special specimens, botanical collections, historical constructions, and points of view; and select 121 plant specimens of interest to obtain the following information: height, diameter at breast height, canopy area, and phenology. The heart of Terra Nostra Garden has its origins in the 1786 summer house of Thomas Hickling. Trees' age estimation enabled to link the sampled trees to different garden historical periods supporting an apparent pattern of plantation from West to East and from North to South explained by the land acquisitions made sequentially by the Viscount and his son the Marquis. The oral tradition referring the *Quercus robur* as the oldest tree, already present in Thomas Hickling Garden, was confirmed (255 years) by the Viscount Duarte Borges da Câmara Medeiros, as well the plantation of at least one *Araucaria* near the tank (*Araucaria bidwillii*). Besides *Quercus robur*, we linked two more specimens to the Thomas Hickling period. *Araucaria heterophylla*, a species introduced to Kew Gardens in 1793 by Joseph Banks, was planted in the early 1800s at Terra Nostra Garden by Thomas Hickling. Although the Ginkgo Lane has been designed between 1936/37 by Vasco Bensaudé; an older specimen planted by the Marquises' heirs already existed. This study allowed also to identify the tallest *Araucaria heterophylla* in Europe (world fourth place).*

Keywords: Furnas landscape, Geographic Information System, GNSS, Historical gardens, Terra Nostra Garden; total station

1. Introduction

Beyond the quality of their designs and their botanical collections, the gardens' aesthetic value also increases with the beauty and history of the surrounding landscape [1]. Terra Nostra Garden is part of a high aesthetic value volcanic landscape. Many gardens are located on volcanic islands (e.g. Kenroku-en Garden in Kanazawa, Japan), in mainland mountains with origin in volcanic activity (e.g. Queen Elizabeth Park in Vancouver, Canada) [2] or nearby volcanic crater lakes (e.g. the Camperdown Botanical Gardens in Australia) [3]. Yet, when we consider the inside of volcano craters, most of them possess native vegetation and belong to protected areas, as the Ngorongoro Crater in Tanzania [4] or the Ma'anling crater in China [5]. Only a few gardens were built inside volcanic craters like the Koko Head Botanical Garden built in 1958 inside a dry crater in Honolulu, Hawaii [6] and some public and private gardens inside the craters of Sete Cidades Volcano and Furnas Volcano in São Miguel Island [7].

Like Furnas landscape, the history of Terra Nostra Garden is rich, it has more than two centuries of history, a unique landscape architecture, and several botanical collections of worldwide interest. In 2020, Pereira et al. estimated the presence of 691 species, 266 hybrids and 859 cultivars at Terra Nostra Garden [8]. In addition to housing the most comprehensive cycad collection and the Camellia collection—recognized in 2014 with the title of Camellia Garden of Excellence by the International Camellia Society (Fig. 1) [8] - the garden also features several unique elements. These include the only open-air cultivation of *Victoria cruziana* in Europe, the tallest *Araucaria heterophylla* in Europe (ranking fourth worldwide), the rare living fossil *Wollemia nobilis* discovered in Australia in 1994,

several plant cultivars developed exclusively at this site, and thermal baths set amidst the trees and birdsong.

The growth of tourism over the past decade, with 268,044 paid entries recorded at Terra Nostra Garden in 2022 [9], has enabled numerous maintenance, restoration, and innovation actions within the garden. Today, the ongoing improvement and sustainable management of the garden increasingly relies on digital tools that provide accurate and comprehensive data on infrastructure, existing plant specimens, their locations, and the documentation of all phytotechnical practices, which are essential for guiding future management decisions [10].

The scientific and visitor value of the garden is directly proportional to the quality and accessibility of the information it can share with others [11]. Systematizing data related to the garden's botanical heritage and its surrounding landscape is therefore critical to enhancing the visitor experience and securing Terra Nostra's position among the world's most significant botanical gardens.



Fig. 1. Terra Nostra Garden (TNG): A. surrounding landscape; B. Aerial view of the cycad collection (a), and part of the camellia collection (b). C. Camellia cultivar produced by Terra Nostra Head gardener, *Camellia x williamsii* 'Patrícia Bensaude Fernandes'.

Today, Geographic Information Systems (GIS) link data to spatial representations, integrating location information (where objects are situated) with descriptive attributes (what those objects are like). Through GIS-generated reports and maps, curators can make informed decisions based on precise inventories, summaries, and rapid analyses of the status of botanical collections and outstanding management tasks. Moreover, GIS serves as a vital tool for connecting biodiversity researchers with the living collections maintained by botanical gardens, thereby facilitating collaborations aimed at developing or strengthening ex situ conservation efforts [11].

For visitors, plant specimens serve both aesthetic and spatial functions within the overall composition and design of the garden, often sparking curiosity about their names, geographic origins, dimensions, ages, and blooming periods.

Building on these principles, the primary aim of this study is to enhance the scientific and economic value of the historic Terra Nostra Garden. To achieve this goal, we established the following specific objectives: (1) to describe the origin and historical development of Terra Nostra Garden, drawing on published sources, unpublished notes, and age determinations of georeferenced tree specimens; (2) to implement a GIS system linked to walking trails that highlight key points of interest, including notable specimens, botanical collections, historical structures, and scenic viewpoints; and (3) to select and characterize 121 plant specimens of special interest by collecting data on height, diameter at breast height, canopy area, and phenological traits.

2. Methodology

2.1 Origin and evolution of Terra Nostra Garden

The origin and evolution of Terra Nostra Garden were reconstructed through the examination of historical documents, recently published scientific studies, unpublished notes by head gardener Fernando Costa (since 1982), and through the georeferencing, identification, and age determination of plant specimens.

Digital mapping of the trees was carried out using GIS tools.

Specimen identification was based on multiple visits to Terra Nostra Garden, during which digital photographs of selected plants were taken, and, when necessary, plant material was collected. Identification was conducted using floras, online databases, virtual herbaria, and both published [e.g. 12] and unpublished information on Terra Nostra Garden [13]. The identifications covered both *taxa* (named following the International Code of Nomenclature for algae, fungi, and plants) [14] and cultivars (named following the International Code of Nomenclature for Cultivated Plants) [15]. Scientific names were aligned with the Plants of the World Online [16], World Flora Online Consortium [17], and Global Biodiversity Information Facility [18] databases; in cases of conflicting information, original publications and the latest research were consulted. The names of Camellia cultivars were updated according to the International Camellia Register database [19,20].

Specimens' age estimation was made at the Forest Products Laboratory (University of Trás-os-Montes and Alto Douro), through the analysis of wood core samples using an increment borer. For each tree, one or two wood cores from bark to pith were collected at 1.3 m above ground and as perpendicular as possible to the axis of the tree. After drying in an environment of 20°C and 60% RH for 72 hours, the cores were polished with a sequence of sandpaper (between 80 to 900 grains / mm²) to highlight the transverse plane and facilitate the observation of wood cells [21]. The identification of the wood ring boundaries was done by observing the changes and/or type of cells that occur at the end of the rings before the dormancy period of the trees. In the case of softwoods, the demarcation of the rings is usually very easy due to the differences in tracheid's transverse dimensions between the earlywood and the latewood. In hardwoods, however, the demarcation is typically due to the type of porosity and/or variation in fibre thickening or the presence of terminal parenchyma in the latewood [22, 23, 24]. Ring counts and ring width were performed under a Mitutoyo TM-111 measuring microscope with micrometric table (precision displacement of 0.001 mm). The COFECHA software was used to statistically verify the cross dating and the rings' measurement quality [25, 26, 27]. The core samples were not collected at tree basis (where all the rings are present), but rather at 1.30 m above ground level, in order to accurately determine the age of the tree it was necessary to add the estimated number of years it took for the tree to reach a height of 1.30 m under the soil and climatic conditions of the island of S. Miguel.

2.2 GIS implementation

2.2.1 GIS implementation under dense canopies

The GIS implementation relies on georeferentiation of points or areas of interest, i.e., measuring coordinates and linking them to data, in our case, specimens' information or garden management areas. Nowadays, precise, and fast measuring of coordinates is done by the Global Navigation Satellite Systems (GNSS) as Global Positioning System (GPS) and Real Time Kinematics (RTK) networks (like REPRAA, in Azores [28]), turning possible decimeter accuracy to centimeter accuracy, a very good level for GIS purposes. However, tree canopies and trunks increase error and interfere with the reception of the signal broadcast by the satellites [29]. In this work, the issue of dense canopy was overcome using both GNSS and TS. Because TS requires intervisibility, it was necessary to install a dense base marker network. First with the RTK GNSS (Leica® GPS1200+) technique on open and wide areas without vegetation, we obtain georeferenced coordinates for some base markers. Then, using TS equipment (Leica® TCRM 1205) and by positioning a minimum of two GNSS markers, we transported (measured) coordinates from one marker to the others, extending the markers networks. Those markers, with a coordinate average accuracy of about 5 mm, served as base markers for TS positioning and for measuring the specimen coordinates and other landforms or infrastructures over the Terra Nostra Garden. In synthesis, the installed dense base markers network was used as source of base points to set up topographic instruments to measure 3D coordinates of 121 plant specimens in a visit course.

2.2.2 Marker's design, installation, and maintenance

Survey markers must be tightly anchored to the ground and be stable over time. The marker's design must comply with a specific geodetic technique, provide safety in the data acquisition process, offer stiffness and strength to corrosion attack, and allow an easy and rigorous setup of equipment [30].

The design and installation of markers over a large historic garden must also comply with several restrictions and premises. Ideally, markers should be cost-effective, use local materials, be durable, and be easy to install and maintain.

In this case markers' design should also respect the Terra Nostra Garden aesthetics, have low visual impact but be sufficiently visible for the periodical actions of maintenance. The markers' design must consider the constant passage of visitors and agricultural machinery, storms occurrence, high rainfall, and high relative humidity values throughout the year.

The markers' installation and maintenance should also prevent tree damage and consider actual and future road improvements or maintenance; in fact, markers should be easy to access and be preferentially located along the garden paths.

In Terra Nostra Garden the permanent markers were built with reinforced concrete and stainless-steel screws, materials which are considered resistant and low-cost. To hide the visible part of the markers on the surface of the paths and garden beds, it was necessary to find a resistant material, framed with the surrounding landscape; thus, we opted for a basaltic stone cover (Fig. 2). This volcanic stone is also used in the garden infrastructures and its porosity and surface voids serve as substrate for mosses and lichens development, turning the markers almost imperceptible with time. Meanwhile, the grey to black colour of basalt rock also contributes for camouflaging the marker top piece.

In this study, between June to August 2019, a total of 46 markers were installed. After one year of use, just two markers suffer partial damage and were later restored.

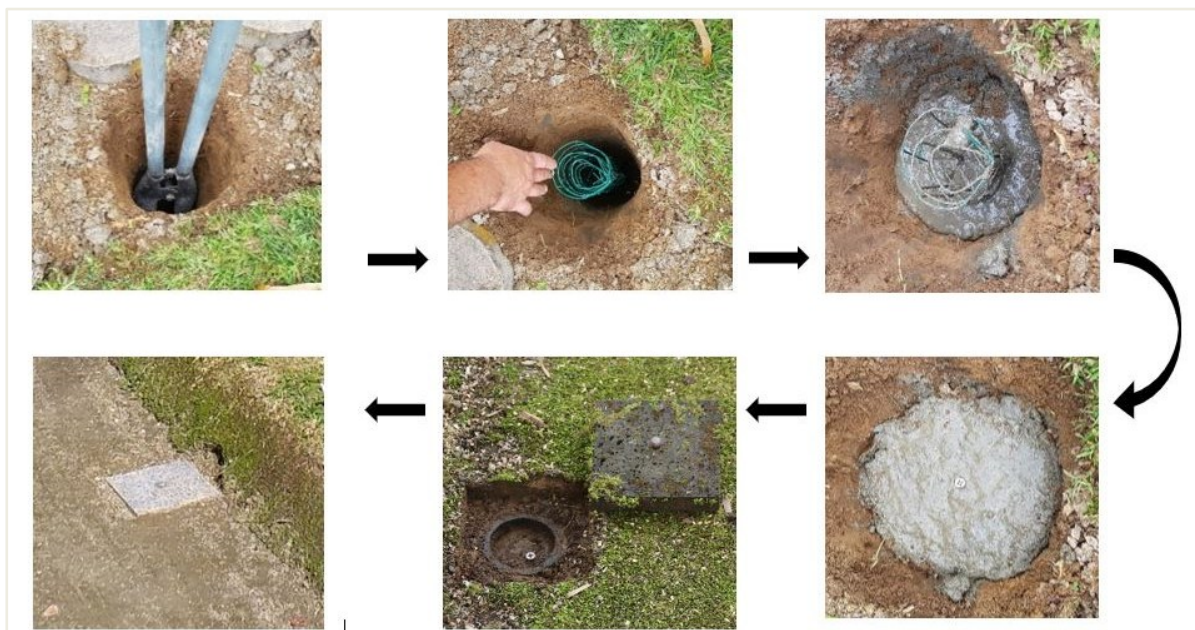


Fig. 2. Marker construction sequence: an iron net is placed in a 20 cm diameter, 60 cm deep hole made with a manual auger. The hole is filled with cement slurry and a stainless bolt is inserted in a central position. For aesthetic reasons, after cement drying, the hole is covered with a square slab of local basaltic rock with a central stainless-steel bolt as a handle, supported by a ring made of PVC pipe. Finally, soil is added to the slab sides.

2.2.3 Specimens georeferentiation

The base markers surveys were done from September 2019 to July 2020, using two different techniques: RTK-GNSS and TS. RTK-GNSS technique was firstly applied on seven markers; the remaining markers, which totals 39, were surveyed with TS technique. During specimens' surveys, the visual obstruction issue from a few base markers to tree location was overcome by making offset points with elevated reflectors (Fig. 3). The base marker network allowed the georeferencing of 121 specimens using the TS technique.



Fig. 3. Data acquisition with Total Station technique and at right an offset point with reflector elevation.

2.3 Selecting and gathering information about 121 plant specimens

2.3.1 Specimens' selection

A group of 121 specimens planted along the walking trails was selected for georeferencing and data collection on morphometry and phenology and when possible, age determination. The criteria used to select those specimens included old specimens (e.g. *Quercus robur* L.), tall specimens (e.g. *Araucaria heterophylla* (Salisb.) Franco), specimens with visually appealing features (e.g. bark of *Melaleuca leucadendra* (L.) L.), and unusual specimens that belong to the camellia, cycad, and fern collections.

2.3.2 Specimens' morphometry

The estimation of specimens' height was directly through an extendable telescopic pole and indirectly with a Vertex laser ® VL400 hypsometer. The highest tree on the garden (specimen number 16) was measured with hypsometer (accuracy 0.1 m) and Total Station (accuracy about 5 mm) [31].

The trunk diameter at breast height was calculated by measuring the perimeter with a tape around trunk at 1.30 m height; to bifurcated trees below the 1.30 m level, the perimeter was measured at 1.30 m in height from the trunk with the biggest perimeter [32].

The shrub or tree canopy area was measured in four perpendicular directions (North, South, West, and East) with a PVC increment pole or metric tape, horizontally in front of the trunk [33].

2.3.3 Specimens' phenology

Since species can vary their behaviour according to the latitude that they are planted (e.g. *Metrosideros excelsa*) but also, because we can find differences between specimens planted at the same place (e.g. *Brachychiton acerifolius*), the most important phenological events regarding leaves and reproductive structures were registered monthly for each specimen over a 1-year period.

3. Results

3.1 Origin and evolution of Terra Nostra Garden

The origins of the Terra Nostra Garden trace back to one of the pioneers of orange production and export in the Azores: Thomas Hickling [34]. In 1770, Hickling - who would later become the U.S. Vice Consul in the Azores - visited the Furnas valley for the first time (Fig. 4A). According to an unpublished letter written by his son, Thomas Hickling Jr., the acquisition of the Furnas property took place around 1782 [34].

Between 1782 and 1786, Hickling constructed the first summer house at Furnas, as documented by the visit of his American daughter, Catherine Hickling, in 1786 (Fig. 4B) [35]. On May 20, 1786, the so-called "Yankee Hall," a single-story residence built on an elevated site, was completed. A staircase of 50 steps connected the house to a fishpond, which featured a boat, and a small islet adorned with a weeping willow. By August of that year, Hickling had added a small bridge to the islet and a white balustrade around the pond. The approach to the house was lined with a hedge of myrtles and five elm trees [35]. The earliest known illustration of this ensemble dates to 1839, published by the Bullar brothers (Fig. 5) [37].



Fig. 4. A. Rock carved by Hickling with his name and year on his first visit to Furnas in 1770. B. Garden description was made by Catherine Greene Hickling (Thomas Hickling's daughter) when she first saw the property on May 20th, 1786 [36].

Thus, the heart of Terra Nostra Garden can be traced to Hickling's 1786 summer residence. The property subsequently passed to Thomas Hickling Jr. in 1834, then to Duarte Borges da Câmara de Medeiros, Viscount of Praia, in 1848, and later to his son, António Borges Medeiros Dias da Câmara e Sousa, Marquis of Praia and Monforte, who owned it from 1872 to 1913 [34]. In 1933, the Terra Nostra Society, under the leadership of Vasco Bensaude, acquired the 12.5-hectare estate from the heirs of the Marquises of Praia and Monforte, with the goal of establishing the first purpose-built hotel in the Azores; the hotel officially opened in 1935 (Fig. 6) [12]. To enhance the grounds, the Scottish gardener John McEnroy, trained at the Royal Botanic Gardens, Kew, was hired. Two years later, the Society reopened the adjacent botanical garden, naming it Terra Nostra Park [12].

The garden weathered two particularly challenging periods: the Second World War (1939–1945) and the Portuguese Carnation Revolution (1974), during which the Bensaude Group had to diversify its commercial activities to navigate economic difficulties [12]. It was only in 1990, during a period of renewed investment, that a major intervention took place to assess the phytosanitary status of approximately 2,500 trees [12]. Since then, the garden has undergone regular maintenance and restoration under the leadership of the current head gardener, Francisco Costa, who has established new plant collections and upgraded the entire water system, ensuring a constant temperature of 37°C throughout the year in the main tank and two additional thermal pools.

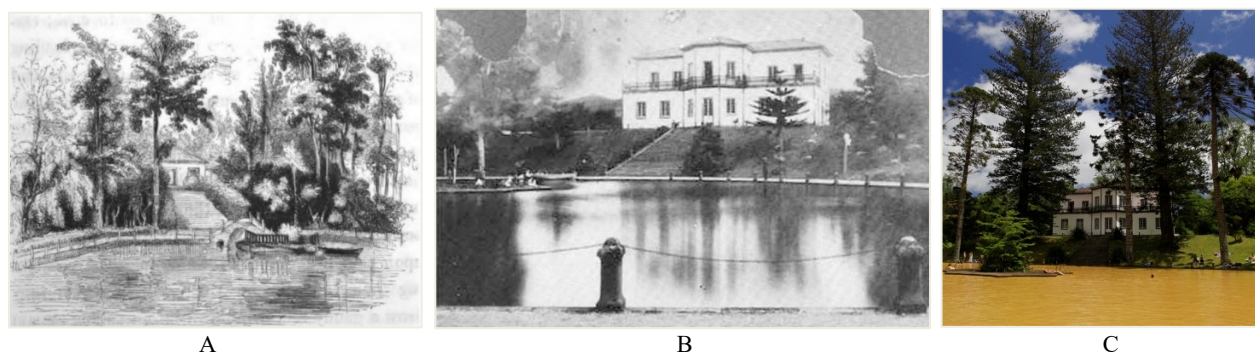


Fig. 5. The tank: A. Thomas Hickling summer House in 1839 [37]; B. Marquis of Praia and Monforte house circa 1900 [38]; C. Terra Nostra Garden Botania Hall [39].

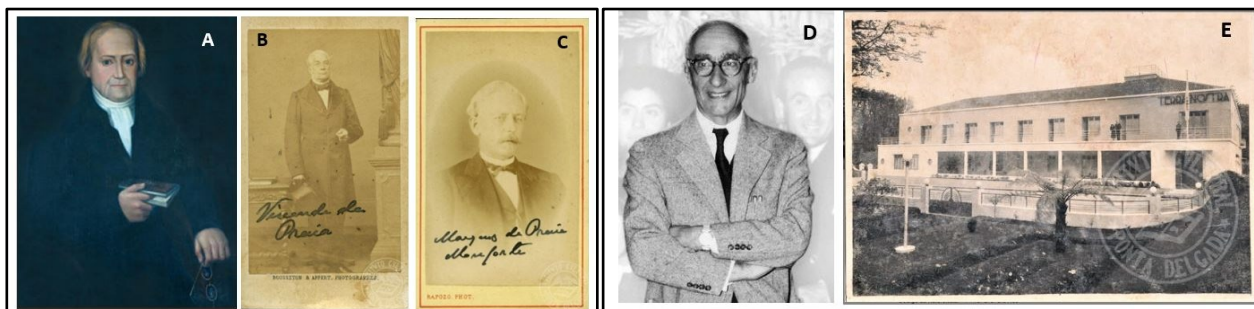


Fig. 6. Terra Nostra property owners between: A. 1782-1834 - Thomas Hickling [40]; B. 1848-1872 - Viscount of Praia Duarte Borges da Câmara de Medeiros [41]; C. 1872-1913 - Marquis António Borges Medeiros Dias da Câmara e Sousa [42]; D. 1933-1967 - Vasco Elias Bensaude [43]; E. Hotel Terra Nostra in 1935 [44].

The key additions to the garden following Thomas Hickling's acquisition of the land in 1782 are summarized chronologically in table 1. Trees' age estimation enabled to link the sampled trees to different garden historical periods (table 2, Fig. 7). Regarding previous information, trees' age estimation supported an apparent pattern of plantation from West to East and from North to South (Fig. 8) probably explained by the land acquisitions made sequentially by the Viscount and his son the Marquis; the oral tradition referring the *Quercus robur* as the oldest tree, already present in Thomas Hickling Garden was confirmed, as well the plantation of at least one araucaria near the tank (*Araucaria bidwillii*) by the Viscount Duarte Borges da Câmara Medeiros (table 1 and table 2).

Besides *Quercus robur*, we linked 2 more trees to the Thomas Hickling period; not surprisingly the native American *Liriodendron tulipifera* was also planted by the American Thomas Hickling. A new finding is that *Araucaria heterophylla*, a species introduced to Kew Gardens in 1793 by Joseph Banks, was planted in the early 1800s at Terra Nostra Garden by Thomas Hickling. As no written records defining the original boundaries of Thomas Hickling's property have been found, the current locations of *Quercus robur*, *Araucaria heterophylla*, and *Liriodendron tulipifera* serve as valuable indicators of the area likely comprising the original estate (Fig. 8).

Besides *Araucaria bidwillii* near the tank, it was also possible to link two other trees to the Viscount Duarte Medeiros: *Carya illinoensis* in a central position of the present garden area, and more important *Platanus orientalis* in almost the extreme Est limit of the present garden area (Fig. 8). Twelve of the sampled trees are centenary trees linked to the Marquis António Sousa, but since we have no acknowledgement that its heirs increased the garden area seven more centenary specimens were added to give us a better definition of the garden limits during their period, specially to the south, with the specimens of *Cryptomeria japonica* 'Elegans' (129 years), *Ginkgo biloba* (106 years) and a specimen of *Camellia japonica* (113 years). Although the Ginkgo Lane has been designed between 1936/37 by Vasco Bensaude (supported by the Ginkgo specimen 77, from 1942); an older specimen panted by the Marquises' heirs already existed (specimen A2, Table 2). None of the sampled specimens located in the southern part of the garden is a centenary specimen, thus all the sampled trees were already planted by Terra Nostra Society or Bensaude Group (Fig. 8).

Tab. 1.a. Terra Nostra Garden: Timeline actions.

Property owners	Years	Action
Thomas Hickling (1782-1834)	1782	Property acquisition [34].
	1786	The Yankee Hall: One storey summer house with stairs leading to a freshwater tank with fishes and a bridge leading small island with a weeping willow. Elms and myrtles planted [35].
Thomas Hickling Jr. (1834-1848)	1834	Inherited property [45].
Viscount Duarte Borges da Câmara Medeiros (1848-1872)	1848	Property acquisition [12, 34].
	1852-1854	Park House - one storey house rebuilt [12, 34].
	1852-1854	Probably guidance from the English Gardener William Webster [12, 34].
		Hickling tank enlargement [12, 34].
		Araucarias planted around the tank [12, 34].
	1860-1870	Acquisition of neighbouring lands [12, 34].
		Palm lane [12, 34].
Marquis António Borges Medeiros Dias da Câmara e Sousa (1872-1913)	1872	Acquisition of neighbouring lands [12, 34].
	1872	Park House rebuilt – two storey house [12, 34].
	1876-79	English Gardener Milton [12, 34].
	1896	Obelisk [12, 34].
	1889	Neo Palladian pavilion [12, 34].
	1872-1900	Probably guidance from a French hydraulic engineer in the water drainage system work [12, 34].
		Serpentine water feature with a tank included [12, 34].
		Garden grotões [12, 34].
		Star shaped tank [12, 34].
		Lover's fountain [12, 34].
		Marble planter pots on columns [12, 34].
		Stone railings [12, 34].
		Iron garden benches [12, 34].
		Croquet court [12, 34].
		Stone bridges over the yellow stream [12, 34].
		Entrance with wrought iron gate, limestone pilasters and walls at the edge of the garden [12, 34].

Tab. 1.b. Terra Nostra Garden: Timeline actions (continuation).

Property owners	Years	Action
Marquises' heirs (1913-1933)	1913	Inherited property [12].
	1933	Park House and tank acquisition [12].
	1933	Scottish Gardener John McEnroy is hired [12].
Vasco Elias	1933-1935	Park House renovation [12].
Bensaude	1933-1935	Tank renovation into a thermal pool [12].
-Terra Nostra	1935	Terra Nostra Hotel inauguration [12].
Society -	1936	Garden acquisition [12].
(1933-1967)	1936-1937	Garden renovation [12].
	1936-1937	Volcanic water lake [12].
	1936-37	Ginkgo lane [12].
	1937	Garden reopening [12].
Filipe Bensaude.	1970	Thomas Hickling bust. [46]
Bensaude Group	1982	Fernando Costa is hired as Gardener [13].
(1967-1990)	1986	Wood bridge over the water serpentine [13].
	1990	Terra Nostra Garden restauration proposal [12,13].
	1991	The Azorean Gardener Francisco Costa is hired as head gardener [12,13].
	1991	Oral tradition: <i>Quercus robur</i> is the oldest tree.
	1991	Garden renovation by the English Horticulturist David Sayers and Fernando Costa [12,13].
	1991	Creation of plant nurseries [13].
	1992	Evaluation of trees phytosanitary status by the arboriculturist Richard Green [13].
	1993	Serpentine's wood bridge replaced by a concrete bridge covered with irregular stones [13].
	1993	<i>Vireya</i> garden [13].
	1996-1998	Volcanic water lake renovation (island, pathway to the margin, waterfall from the serpentine) [13].
	1994	Gutter and small dam in the serpentine's lake [13].
	1994	The head gardener starts collecting different specimens of camellia [13].
	1995	Fern collection [13].
Joaquim Bensaude.	1994	Collection of Azorean endemic trees and shrubs.
Bensaude Group.	1995	Fern collection [13].
(1990-2014)	1998	Flower Garden [13].
	1999	Zoomorphic sculptures [13].
	2000	<i>Cycadales</i> garden [13].
	2000	New palm grove [13].
	2004	<i>Camellia</i> garden [13].
	2005	Serpentine's bridge renovation [13].
	2007	<i>Wollemia nobilis</i> [13].
	2008	Water network renovation: thermal water pool with constant temperature of 37°C throughout the year [13].
	2008	Hickling Tank with hot water throughout the year [13].
	2008	Creek of ferric iron water, next to the fern collection, enlarged [13].
	2009	Bamboo garden [13].
	2011	Bromeliad garden [13].
	2012	<i>Victoria cruziana</i> tank [13].
	2015	Vasco Bensaude Bust [13].
	2015	1 st Natural jacuzzi [13].
	2015	Path with basalt stones around the thermal pool [13].
	2016	2 nd Natural jacuzzi [13].
	2016	Flower Garden renovation [13].
	2017	Aquatic plants collection in a new lake [13].
Patrícia Bensaude.	2017	Renovation of garden plant nurseries [13].
Bensaude Group.	2018	Endemic & Native Flora Garden renovation [13].
(2014-present)	2017	Orchid collection [13].
	2018	Serpentine with two waterfalls in basalt stone [13].
	2018	Wood umbrellas around the thermal water pool (the Hickling tank) [13].
	2020	Volcanic water lake renovation (island, pathway, and margins) [13].
	2021	Park House refurbishment [13].
	2023	Ticket offices and jacuzzi renovation [13].
	2024	Hot water tank retrofitting [13]

Tab. 2. Specimens estimated age.

ID	Scientific name	Estimated age in 2023 (years)	Alive since (date)	Probably planted by (property owners)
121	<i>Quercus robur</i> L.	255	1768	Vice Consul
16	<i>Araucaria heterophylla</i> (Salisb.) Franco	223	1800	Thomas Hickling
83	<i>Liriodendron tulipifera</i> L.	196	1827	(1782-1834)
21	<i>Carya illinoensis</i> (Wangenh.) K.Koch	177	1846	Viscount
86	<i>Platanus orientalis</i> L.	174	1849	Duarte Borges da
13	<i>Araucaria bidwillii</i> Hook.	171	1852	Câmara Medeiros (1848-1872)
84	<i>Cryptomeria japonica</i> (Thunb. ex L.f.) D.Don 'Elegans'	150	1873	
73	<i>Cunninghamia lanceolata</i> (Lamb.) Hook.	149	1874	
10	<i>Quercus palustris</i> Münchh.	145	1878	
11	<i>Araucaria columnaris</i> (G.Forst.) Hook.	144	1879	
109	<i>Taxodium distichum</i> (L.) Rich var. <i>imbricarium</i> (Nutt.) Croom	144	1879	Marquis
82	<i>Quercus rotundifolia</i> Lam.	137	1886	Antônio Borges
A19	<i>Liriodendron tulipifera</i> L.	133	1890	Medeiros Dias da
17	<i>Ocotea foetens</i> (Aiton) Baill.	130	1893	Câmara e Sousa. (1872-1913)
34	<i>Cryptomeria japonica</i> (Thunb. ex L.f.) D.Don 'Elegans'	129	1894	
6	<i>Platanus</i> × <i>hispanica</i> Mill. ex Münchh.	129	1894	
A5	<i>Araucaria heterophylla</i> (Salisb.) Franco	124	1899	
95	<i>Pittosporum undulatum</i> Vent.	123	1900	
A9	<i>Camellia japonica</i> L.	113	1910	
A17	<i>Liriodendron tulipifera</i> L.	113	1910	
A2	<i>Ginkgo biloba</i> L.	106	1917	Marquises' heirs.
108	<i>Magnolia grandiflora</i> L.	106	1917	[1913-1933]
110	<i>Tilia cordata</i> Mill.	106	1917	
106	<i>Sequoia sempervirens</i> (D.Don) Endl.	105	1918	
A10	<i>Camellia japonica</i> L.	101	1922	
12	<i>Araucaria angustifolia</i> (Bertol.) Kuntze	96	1927	
A12	<i>Camellia japonica</i> L.	94	1929	
107	<i>Taxodium distichum</i> (L.) Rich. var. <i>distichum</i>	94	1929	
74	<i>Fagus sylvatica</i> L. 'Purpurea'	94	1934	
A18	<i>Quercus palustris</i> Münchh.	86	1937	
A11	<i>Camellia japonica</i> L. 'Vittoria Falsoi'	82	1941	
77	<i>Ginkgo biloba</i> L.	80	1943	
14	<i>Acer palmatum</i> Thunb.	79	1944	Vasco Elias
A15	<i>Liriodendron tulipifera</i> L.	79	1944	Bensaude. Terra
A8	<i>Camellia japonica</i> L.	76	1947	Nostra Society.
A20	<i>Araucaria angustifolia</i> (Bertol.) Kuntze	75	1948	[1933-1967]
26	<i>Castanea sativa</i> Mill.	73	1950	
85	<i>Quercus suber</i> L.	72	1951	
56	<i>Ceiba speciosa</i> (A.St.-Hil., A.Juss. & Cambess.) Ravenna	71	1952	
A16	<i>Ocotea foetens</i> (Aiton) Baill.	71	1952	
A13	<i>Camellia japonica</i> L.	66	1957	
A4	<i>Camellia japonica</i> L.	66	1957	
A6	<i>Cryptomeria japonica</i> (Thunb. ex L.f.) D.Don 'Elegans'	64	1959	
A14	<i>Chamaecyparis pisifera</i> (Siebold & Zucc.) Endl.	55	1968	Filipe Bensaude.
A3	<i>Ginkgo biloba</i> L.	55	1968	Bensaude Group.
A1	<i>Cryptomeria japonica</i> (Thunb. ex L.f.) D.Don	53	1970	(1967-1990)



Fig. 7. Position and identification numbers of trees sampled for age estimation in Terra Nostra Garden. Red dots: trees planted during Thomas Hickling period (1782-1834). Orange dots: trees planted during Viscount Duarte Borges da Câmara Medeiros period (1848-1872). Yellow dots: trees planted during Marquis António Borges Medeiros Dias da Câmara e Sousa period (1872-1913). Green dots: trees planted during Marquises' heirs' period (1913-1933). Blue dots: trees planted during Vasco Elias Bensaude period (1933-1967). Dark blue dots: trees planted during Filipe Bensaude-Bensaude Group period (1967-1990).

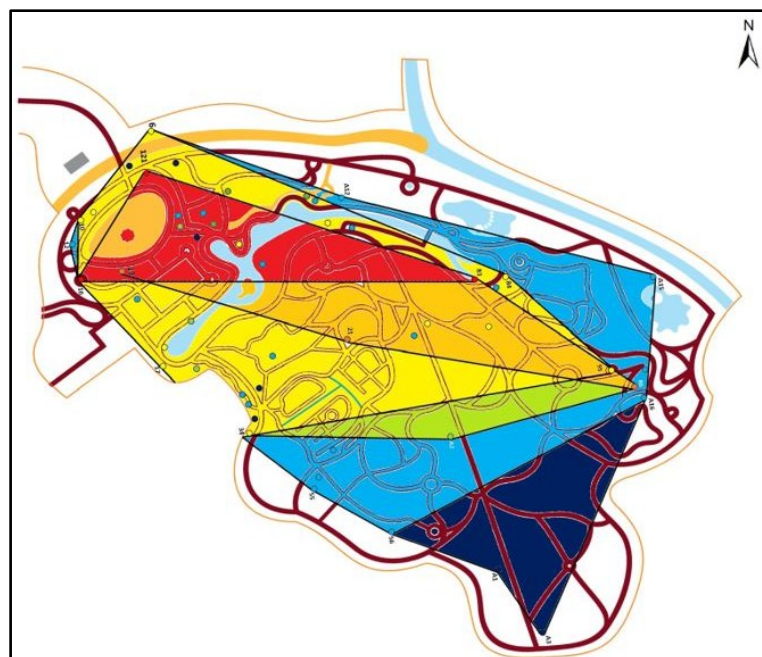


Fig. 8. Terra Nostra Garden; minimum property areas for each property owner inferred only by tree age estimation (polygons drawn using the outermost trees from the same period). Red area: Thomas Hickling period (1782-1834). Orange area: Viscount Duarte Borges da Câmara Medeiros period (1848-1872). Yellow area: Marquis António Borges Medeiros Dias da Câmara e Sousa period [1872-1913]. Green area: Marquises' heirs' period (1913-1933). Blue area: Vasco Elias Bensaude period (1933-1967). Dark blue area: Filipe Bensaude- Bensaude Group period (1967-1990).

3.2 GIS: Linking Specimens UTM coordinates to information

UTM coordinates were used to define garden management areas and measure precise 3D coordinates of 121 plant specimens on a visit course. Tables 3.a, 3.b, and 3.c links the UTM coordinates to specimens' information: scientific name, height, diameter at breast height and canopy area. Tables 4.a to 4.f adds phenological information about the 121 georeferenced specimens along the year. UTM coordinates were obtained after the installation of a dense topographic network of aesthetic markers.

Figures 9a, to 9e displays the network of topographic markers installed and the physical structures needed to use as base points to setup topographic instruments, as well the 121 georeferenced plant specimens with their canopy areas.



Fig. 9a. Terra Nostra Garden network of topographic markers and 121 georeferenced specimens. See figures 9b to 9e for details.



Fig. 9b, c, d, e. Terra Nostra Garden network of topographic markers: Red Star symbols for GNSS sites; blue circle symbols for TS sites. Georeferenced specimens: 121 green dots. Specimens' mean canopies areas: green circles. This area corresponds to rectangle 1-4 of figure 9a.

Tab. 3.a. Linking UTM coordinates to specimens' information. UTM coordinates (X - Easting, Y - Northing, H - Height). N - Specimen Number; H - Specimen Height; DBH - Diameter at Breast Height; CA - Canopy Area.

UTM Coordinates			N	Scientific name	H	DBH	CA
X (m)	Y (m)	H (m)			(m)	(cm)	(m ²)
648339.85	4181895.34	201.06	1	<i>Metrosideros robusta</i> A.Cunn.	31.7	64	305.3
648348.47	4181893.12	200.48	2	<i>Howea forsteriana</i> (F.Muell.) Becc.	19	21	13.5
648382.91	4181889.72	200.39	3	<i>Dracaena draco</i> (L.) L. subsp. <i>draco</i>	3	28	8.6
648390.89	4181884.82	199.94	4	<i>Livistona chinensis</i> (Jacq.) R.Br. ex Mart.	12.1	34	16.5
648394.59	4181887.56	200.61	5	<i>Juniperus bermudiana</i> L.	22.5	103	119
648425.66	4181903.01	201	6	<i>Platanus</i> × <i>hispanica</i> Mill. ex Münchh.	40.4	131	343.7
648386.56	4181865.94	199.3	7	<i>Strelitzia nicolai</i> Regel & K.Koch	12.4	-	99.6
648397.7	4181871.89	198.51	8	<i>Acer henryi</i> Pax	8.5	28	17.5
648404.7	4181852.98	198.44	9	<i>Ulmus minor</i> Mill.	18.4	80	94.2
648362.49	4181819.64	199.26	10	<i>Quercus palustris</i> Münchh.	32.2	99	217.3
648380.66	4181815.79	200.82	11	<i>Araucaria columnaris</i> (G.Forst.) Hook.	36.3	108	24.6
648370.39	4181792.86	200.57	12	<i>Araucaria angustifolia</i> (Bertol.) Kuntze	16	46	34.2
648408.89	4181776.27	200.92	13	<i>Araucaria bidwillii</i> Hook.	31.9	105	65.8
648417.26	4181755.89	206	14	<i>Acer palmatum</i> Thunb.	13.9	54	114.5
648392.13	4181751.94	202.98	15	<i>Metrosideros excelsa</i> Sol. ex Gaertn.	22.6	168	147.1
648375.1	4181767	202.07	16	<i>Araucaria heterophylla</i> (Salisb.) Franco	52	208	196.1
648464.42	4181804.76	203.85	17	<i>Ocotea foetens</i> (Aiton) Baill.	25.1	131	120.8
648507.96	4181747.97	200.22	18	<i>Melaleuca leucadendra</i> (L.) L.	21.7	80	86
648525.99	4181800.67	200.79	19	<i>Phoenix dactylifera</i> L.	13.7	13	26.4
648559.21	4181770.05	202.32	20	<i>Dendrocalamus giganteus</i> Munro	7	8	16.3
648574.03	4181725.49	205.06	21	<i>Carya illinoensis</i> (Wangenh.) K.Koch	44	108	317.3
648557.02	4181729	204.95	22	<i>Frangula azorica</i> Grubov	6	10	5.7
648547.81	4181713.03	205.05	23	<i>Ilex perado</i> subsp. <i>azorica</i> Tutin	5.4	26	35
648560.51	4181716.67	204.99	24	<i>Prunus lusitanica</i> L. subsp. <i>azorica</i> (Mouill.) Franco	4.6	21	15.2
648529.47	4181699.97	206.68	25	<i>Erica azorica</i> Hochst. ex Seub.	7.8	24	14.5
648524.31	4181708.43	206.69	26	<i>Castanea sativa</i> Mill.	12.3	66	88.5
648509.51	4181694.94	207.38	27	<i>Azorina vidalii</i> (H.C.Watson) Feer	0.6	-	0.1
648513.88	4181694.45	206.95	28	<i>Euphorbia stygiana</i> H. C. Watson subsp. <i>stygiana</i>	0.6	-	0.5
648515.83	4181694.01	207.06	29	<i>Angelica lignescens</i> Reduron & Danton	0.6	-	0.7
648518.86	4181684.75	207.86	30	<i>Rumex azoricus</i> Rech.f.	0.7	-	1.5
648518.63	4181671.79	206.35	31	<i>Camellia japonica</i> L. 'Alberto Allen'	9.9	23	23
648506.32	4181645.95	207.19	32	<i>Cordyline australis</i> (G.Forst.) Endl.	16	24	100.1
648502.12	4181643.93	206.9	33	<i>Tipuana tipu</i> (Benth.) Kuntze	25.1	76	331.4
648507.87	4181640.9	206.95	34	<i>Cryptomeria japonica</i> (Thunb. ex L.f.) D.Don	22	99	36.6
648561.19	4181695.46	211.54	35	<i>Ceratozamia kuesteriana</i> Regel	1.3	-	2.5
648533.31	4181659.1	211.24	36	<i>Cycas circinalis</i> L.	2.4	25	6.2
648528.75	4181678.91	212.15	37	<i>Cycas multipinnata</i> C.J.Chen & S.Y.Yang	3	41	15.2
648562.8	4181687.33	207.64	38	<i>Encephalartos ferox</i> G.Bertol.	2.3	41	7.1
648543.92	4181685.69	205.47	39	<i>Encephalartos friderici-guilielmi</i> Lehm.	1.4	44	3.1
648570.93	4181689.7	210.94	40	<i>Encephalartos kisambo</i> Faden & Beentje	2.5	43	12.6
648550.3	4181692.15	207.01	41	<i>Encephalartos natalensis</i> R.A.Dyer & Verdoorn	2.4	48	7.1
648537.17	4181694.47	212.08	42	<i>Encephalartos nubimontanus</i> P.J.H.Hurter	1.6	35	5.3
648546.43	4181672.32	207.07	43	<i>Encephalartos paucidentatus</i> Stapf & Burtt Davy	3.5	62	11.3
648552.82	4181674.16	207.24	44	<i>Encephalartos woodii</i> Sander	1.5	32	4.9
648545.62	4181676.92	206.14	45	<i>Macrozamia spiralis</i> (Salisb.) Miq.	2.4	-	8
648549.36	4181685.01	206.2	46	<i>Zamia furfuracea</i> L.f. ex Aiton	1.2	-	2
648542.03	4181684.65	206.58	47	<i>Wollemia nobilis</i> W.G.Jones, K.D.Hill & J.M.Allen	5.7	11	1.9

Tab. 3.b. Linking UTM coordinates to specimens' information. UTM coordinates (X - Easting, Y - Northing, H - Height). N - Specimen Number; H - Specimen Height; DBH - Diameter at Breast Height; CA - Canopy Area (continuation).

UTM Coordinates			N	Scientific name	H (m)	DBH (cm)	CA (m ²)
X (m)	Y (m)	H (m)					
648540.3	4181652	206.46	48	<i>Camellia reticulata</i> Lindl. 'Captain Rawes'	5.2	17	24.6
648569.19	4181666.87	206.06	49	<i>Camellia reticulata</i> Lindl. x <i>Camellia japonica</i> L. 'Jean Pursel'	3.7	15	11.6
648576.26	4181683.86	206.04	50	<i>Camellia sasanqua</i> Thunb. x <i>Camellia reticulata</i> Lindl. 'Dream Girl'	9.4	14	14.9
648567.17	4181643.41	206.52	51	<i>Psidium cattleianum</i> Afzel. ex Sabine	8.7	25	28.3
648575.09	4181647.4	206.2	52	<i>Camellia japonica</i> L. 'Mathotiana Rubra'	4.5	13	15.2
648583.89	4181653.8	205.75	53	<i>Camellia japonica</i> L. 'Augusto Leal de Gouveia Pinto'	4.6	11	16.6
648567.13	4181614.98	206.55	54	<i>Acer pseudoplatanus</i> L.	22.6	55	51.1
648563.82	4181611.23	206.69	55	<i>Pinus pinea</i> L.	25	61	62.8
648596.09	4181586.91	207.73	56	<i>Ceiba speciosa</i> (A.St.-Hil., A.Juss. & Cambess.) Ravenna	36.5	146	307
648612.85	4181688.76	204.28	57	<i>Camellia japonica</i> L. 'Black Magic'	2.6	10	1.9
648581.95	4181706.84	206.14	58	<i>Liquidambar styraciflua</i> L.	16	38	67.2
648592.37	4181699.92	205.43	59	<i>Oxydendrum arboreum</i> (L.) DC.	10.5	20	15.6
648592.78	4181685.3	208.25	60	<i>Acer negundo</i> L. 'Variegatum'	11.7	23	71.6
648584.01	4181687.9	210.61	61	<i>Camellia</i> 'Night Rider'	3.2	11	8.2
648596.14	4181695.07	204.85	62	<i>Camellia rusticana</i> Honda x <i>Camellia lutchuensis</i> T.Itô 'Fragrant Pink'	4.2	11	7.5
648577.11	4181708.42	204.99	63	<i>Camellia</i> x <i>williamsii</i> W.W.Sm. 'Water Lily'	5.5	13	11.9
648594.22	4181724.73	209.35	64	<i>Camellia</i> 'Ki-rence'	2.5	7	12.9
648603.9	4181710.51	208.98	65	<i>Camellia</i> 'Pink Granthamiana'	3.4	8	9.8
648602.83	4181724.53	203.85	66	<i>Camellia sasanqua</i> Thunb. 'Hugh Evans'	3.2	12	12.6
648578.33	4181737.46	204.01	67	<i>Camellia</i> x <i>vernalis</i> 'Yuletide'	1.8	4	5.5
648610.95	4181759.58	203.53	68	<i>Camellia amplexicaulis</i> (Pit.) Cohen-Stuart	1.8	2	2.6
648600.97	4181774.42	203.64	69	<i>Camellia azalea</i> C.F.Wei	1.6	3	1.3
648593.82	4181761.95	202.31	70	<i>Camellia petelotii</i> (Merr.) Sealy var. <i>petelotii</i>	3.2	9	13.4
648583.37	4181761.95	202.31	71	<i>Syagrus romanzoffiana</i> (Cham.) Glassman	18.5	27	24.6
648583.37	4181775.84	202.53	72	<i>Chusquea coronalis</i> Soderstr. & C.E.Calderon	4.3	1	25
648576.15	4181774.46	202.74	73	<i>Cunninghamia lanceolata</i> (Lamb.) Hook.	24.6	119	99
648592.72	4181805.96	203.92	74	<i>Fagus sylvatica</i> L. 'Purpurea'	24	75	121.1
648608.32	4181796.51	204.2	75	<i>Archontophoenix cunninghamiana</i> (H.Wendl.) H.Wendl. & Drude	10.2	24	17.1
648623.82	4181795.61	204.25	76	<i>Butia capitata</i> (Mart.) Becc.	2.5	33	19.6
648627.36	4181733.35	205.28	77	<i>Ginkgo biloba</i> L.	34	64	73.9
648732.9	4181694.8	206.1	78	<i>Phoenix canariensis</i> Chabaud	17.1	64	25.5
648808.56	4181737.39	193.45	79	<i>Aesculus pavia</i> L.	2.7	11	18.8
648733.68	4181698.41	206.06	80	<i>Rhododendron arboreum</i> Sm.	6	17	11.9
648709.4	4181719.37	204.05	81	<i>Rhopalostylis sapida</i> (Sol. ex G.Forst.) H.Wendl. & Drude	6.5	27	55.4
648685.55	4181738.47	203.62	82	<i>Quercus rotundifolia</i> Lam.	44.3	105	94.8
648675.94	4181772.72	203.4	83	<i>Liriodendron tulipifera</i> L.	50	181	608.1
648693.74	4181782.72	202	84	<i>Cryptomeria japonica</i> (Thunb. ex L.f.) D.Don 'Elegans'	28	78	58.8
648694.65	4181793.13	203.36	85	<i>Quercus suber</i> L.	22.5	111	176.1
648801.17	4181697.06	200.65	86	<i>Platanus orientalis</i> L.	36.2	108	437.4

Tab. 3.c. Linking UTM coordinates to specimens' information. UTM coordinates (X - Easting, Y - Northing, H - Height). N - Specimen Number; H - Specimen Height; DBH - Diameter at Breast Height; CA - Canopy Area (continuation).

UTM Coordinates			N	Scientific name	H	DBH	CA
X (m)	Y (m)	H (m)			(m)	(cm)	(m ²)
648730.47	4181801.82	194.61	87	<i>Quercus phellos</i> L.	14.6	25	52.8
648751.24	4181811.33	193.82	88	<i>Polyspora axillaris</i> (Roxb. ex Ker Gawl.) Sweet	7.6	22	36.3
648776.63	4181793.23	193.46	89	<i>Stewartia sinensis</i> Rehder & E.H. Wilson	7.8	10	26.4
648790.65	4181746.72	192.98	90	<i>Phyllarthron bojeranum</i> DC.	6.8	26	17.8
648811.28	4181727.09	193.47	91	<i>Corymbia ficifolia</i> (F.Muell.) K.D.Hill & L.A.S.Johnson	12.8	29	49.3
648820.98	4181715.21	194.34	92	<i>Corylopsis veitchiana</i> Bean	5.8	-	41
648830.14	4181689.31	197.15	93	<i>Styrax obassia</i> Siebold & Zucc.	12.4	14	27.8
648813.11	4181686.09	199.79	94	<i>Metasequoia glyptostroboides</i> Hu & W.C.Cheng	6.6	20	29.2
648779.41	4181707.98	203.84	95	<i>Pittosporum undulatum</i> Vent.	23	108	265.2
648807.02	4181768.38	193.31	96	<i>Yucca gigantea</i> Lem.	7.5	-	12.3
648766.91	4181815.59	193.42	97	<i>Agathis robusta</i> (C.Moore ex F.Muell.) F.M.Bailey	18.5	26	20
648721.74	4181830.92	193.75	98	<i>Eucalyptus deglupta</i> Blume	17.5	23	20
648637.29	4181868.61	194.84	99	<i>Furcraea selloa</i> K.Koch	6	50	6.2
648639.64	4181863.16	194.61	100	<i>Metrosideros umbellata</i> Cav.	15.8	95	84.9
648627.09	4181871.06	194.73	101	<i>Melaleuca linariifolia</i> Sm.	7.4	118	39
648571.76	4181853.84	195.14	102	<i>Eucalyptus globulus</i> Labill.	40	181	455.2
648544.53	4181863.11	195.11	103	<i>Melaleuca citrina</i> (Curtis) Dum.Cours. 'Splendens'	5.5	-	38.8
648535.22	4181859.91	195.62	104	<i>Bismarckia nobilis</i> Hildebr. & H.Wendl.	3.8	43	15.2
648486.37	4181858.14	195.85	105	<i>Halleria lucida</i> L.	10.2	-	90.3
648478.38	4181843.32	196.4	106	<i>Sequoia sempervirens</i> (D.Don) Endl.	42.8	134	47.2
648461.17	4181827.68	196.84	107	<i>Taxodium distichum</i> (L.) Rich. var. <i>distichum</i>	24.2	100	118.8
648469.31	4181812.29	197.39	108	<i>Magnolia grandiflora</i> L.	12.9	68	117.9
648491.59	4181798.37	197.55	109	<i>Taxodium distichum</i> (L.) Rich var. <i>imbricarium</i> (Nutt.) Croom	27	131	213.8
648537.85	4181837.75	197.5	110	<i>Tilia cordata</i> Mill.	22.5	73	187.5
648494.03	4181836.23	196.24	111	<i>Angiopteris evecta</i> (G. Forst.) Hoffm.	1.6	-	9.6
648506.93	4181848.19	195.85	112	<i>Dicksonia antarctica</i> Labill.	3.5	31	11.8
648488.02	4181835.24	196.28	113	<i>Blechnum gibbum</i> Mett.	1.4	9	1.1
648529.33	4181843.49	195.91	114	<i>Alsophila tricolor</i> (Colenso) R.M.Tryon	3.6	23	15.9
648497.83	4181840.68	196.2	115	<i>Sphaeropteris medullaris</i> (G.Forst.) Bernh.	10	23	13.9
648485.44	4181838.19	196.24	116	<i>Dicksonia squarrosa</i> (G.Forst.) Sw.	5.2	12	4.5
648463.32	4181868.16	196.4	117	<i>Fagus sylvatica</i> L.	32.3	60	96.3
648481.03	4181876.82	195.63	118	<i>Pittosporum undulatum</i> Vent. 'Variegatum'	11.2	58	50
648447.52	4181874.11	196.67	119	<i>Syzygium australe</i> (J.C.Wendl. ex Link) B.Hyland	26.1	67	175
648420.99	4181863.8	197.19	120	<i>Halesia carolina</i> L.	7.3	24	40.7
648414.98	4181844.23	200.65	121	<i>Quercus robur</i> L.	14.3	108	169.1

Tab. 4.a. Phenological events of 121 georeferenced specimens (N - Specimen number) at Terra Nostra Garden from January to December. Leaves: Green = with leaves; Orange = leaf fall; Gray = without leaves. Reproductive structures: Red = Flowers and/or fruits; Yellow = Pollen cones; Dark green = Seed cones; Black = Spores.

N	Specimen identification	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	<i>Metrosideros robusta</i>												
2	<i>Howea forsteriana</i>												
3	<i>Dracaena draco</i> subsp. <i>draco</i>												
4	<i>Livistona chinensis</i>												
5	<i>Juniperus bermudiana</i>												
6	<i>Platanus</i> × <i>hispanica</i>												
7	<i>Strelitzia nicolai</i>												
8	<i>Acer henryi</i>												
9	<i>Ulmus minor</i>												
10	<i>Quercus palustris</i>												
11	<i>Araucaria columnaris</i>												
12	<i>Araucaria angustifolia</i>												
13	<i>Araucaria bidwillii</i>												
14	<i>Acer palmatum</i>												
15	<i>Metrosideros excelsa</i>												
16	<i>Araucaria heterophylla</i>												
17	<i>Ocotea foetens</i>												
18	<i>Melaleuca leucadendra</i>												
19	<i>Phoenix dactylifera</i>												
20	<i>Dendrocalamus giganteus</i>												
21	<i>Carya illinoensis</i>												
22	<i>Frangula azorica</i>												
23	<i>Ilex perado</i> subsp. <i>azorica</i>												
24	<i>Prunus lusitanica</i> subsp. <i>azorica</i>												
25	<i>Erica azorica</i>												
26	<i>Castanea sativa</i>												
27	<i>Azorina vidalii</i>												
28	<i>Euphorbia stygiana</i> subsp. <i>stygiana</i>												
29	<i>Angelica lignescens</i>												
30	<i>Rumex azoricus</i>												

Tab. 4.b. Phenological events of 121 georeferenced specimens (N - Specimen number) at Terra Nostra Garden from January to December. Leaves: Green = with leaves; Orange = leaf fall; Gray = without leaves. Reproductive structures: Red = Flowers and/or fruits; Yellow = Pollen cones; Dark green = Seed cones; Black = Spores. (continuation).

N	Specimen identification	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
31	<i>Camellia japonica</i> 'Alberto Allen'												
32	<i>Cordyline australis</i>												
33	<i>Tipuana tipu</i>												
34	<i>Cryptomeria japonica</i>												
35	<i>Ceratozamia kuesteriana</i>												
36	<i>Cycas circinalis</i>												
37	<i>Cycas multipinnata</i>												
38	<i>Encephalartos ferox</i>												
39	<i>Encephalartos friderici-guilielmi</i>												
40	<i>Encephalartos kisambo</i>												
41	<i>Encephalartos natalensis</i>												
42	<i>Encephalartos nubimontanus</i>												
43	<i>Encephalartos paucidentatus</i>												
44	<i>Encephalartos woodii</i>												
45	<i>Macrozamia spiralis</i>												
46	<i>Zamia furfuracea</i>												
47	<i>Wollemia nobilis</i>												
48	<i>Camellia reticulata</i> 'Captain Rawes'												
49	<i>Camellia reticulata</i> x <i>Camellia japonica</i> 'Jean Purses'												
50	<i>Camellia sasanqua</i> x <i>Camellia reticulata</i> 'Dream Girl'												
51	<i>Psidium cattleianum</i>												
52	<i>Camellia japonica</i> 'Mathotiana Rubra'												
53	<i>Camellia japonica</i> 'Augusto Leal de Gouveia Pinto'												
54	<i>Acer pseudoplatanus</i>												
55	<i>Pinus pinea</i>												
56	<i>Ceiba speciosa</i> (A.St.-Hil., A.Juss. & Cambess.) Ravenna												
57	<i>Camellia japonica</i> 'Black Magic'												
58	<i>Liquidambar styraciflua</i>												
59	<i>Oxydendrum arboreum</i>												
60	<i>Acer negundo</i> 'Variegatum'												

Tab. 4.c. Phenological events of 121 georeferenced specimens (N - Specimen number) at Terra Nostra Garden from January to December.
Leaves: Green = with leaves; Orange = leaf fall; Gray = without leaves. Reproductive structures: Red = Flowers and/or fruits; Yellow = Pollen cones; Dark green = Seed cones; Black = Spores (continuation).

N	Specimen identification	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
61	<i>Camellia</i> 'Night Rider'												
62	<i>Camellia rusticana</i> x <i>Camellia lutchuensis</i> 'Fragrant Pink'												
63	<i>Camellia</i> x <i>williamsii</i> 'Water Lily'												
64	<i>Camellia</i> 'Ki-rence'												
65	<i>Camellia</i> 'Pink Granthamiana'												
66	<i>Camellia sasanqua</i> 'Hugh Evans'												
67	<i>Camellia</i> x <i>vernalis</i> 'Yuletide'												
68	<i>Camellia amplexicaulis</i>												
69	<i>Camellia azalea</i>												
70	<i>Camellia petelotii</i> var. <i>petelotii</i>												
71	<i>Syagrus romanzoffiana</i>												
72	<i>Chusquea coronalis</i>												
73	<i>Cunninghamia lanceolata</i>												
74	<i>Fagus sylvatica</i> 'Purpurea'												
75	<i>Archontophoenix cunninghamiana</i>												
76	<i>Butia capitata</i>												
77	<i>Ginkgo biloba</i>												
78	<i>Phoenix canariensis</i>												
79	<i>Aesculus pavia</i>												
80	<i>Rhododendron arboreum</i>												
81	<i>Rhopalostylis sapida</i>												
82	<i>Quercus rotundifolia</i>												
83	<i>Liriodendron tulipifera</i>												
84	<i>Cryptomeria japonica</i> 'Elegans'												
85	<i>Quercus suber</i>												
86	<i>Platanus orientalis</i>												
87	<i>Quercus phellos</i>												
88	<i>Polyspora axillaris</i>												
89	<i>Stewartia sinensis</i>												

Tab. 4.d. Phenological events of 121 georeferenced specimens (N - Specimen number) at Terra Nostra Garden from January to December.
 Leaves: Green = with leaves; Orange = leaf fall; Gray = without leaves. Reproductive structures: Red = Flowers and/or fruits; Yellow = Pollen cones; Dark green = Seed cones; Black = Spores (continuation).

N	Specimen identification	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
90	<i>Phyllarthron bojeranum</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
91	<i>Corymbia ficifolia</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
92	<i>Corylopsis veitchiana</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
93	<i>Styrax obassia</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
94	<i>Metasequoia glyptostroboides</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
95	<i>Pittosporum undulatum</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
96	<i>Yucca gigantea</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
97	<i>Agathis robusta</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
98	<i>Eucalyptus deglupta</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
99	<i>Furcraea selloa</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
100	<i>Metrosideros umbellata</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
101	<i>Melaleuca linariifolia</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
102	<i>Eucalyptus globulus</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
103	<i>Melaleuca citrina</i> 'Splendens'	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
104	<i>Bismarckia nobilis</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
105	<i>Halleria lucida</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
106	<i>Sequoia sempervirens</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
107	<i>Taxodium distichum</i> var. <i>distichum</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
108	<i>Magnolia grandiflora</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
109	<i>Taxodium distichum</i> var. <i>imbricarium</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
110	<i>Tilia cordata</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
111	<i>Angiopteris evecta</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
112	<i>Dicksonia antarctica</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
113	<i>Blechnum gibbum</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
114	<i>Alsophila tricolor</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
115	<i>Sphaeropteris medullaris</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green

Tab. 4.e. Phenological events of 121 georeferenced specimens (N - Specimen number) at Terra Nostra Garden from January to December. Leaves: Green = with leaves; Orange = leaf fall; Gray = without leaves. Reproductive structures: Red = Flowers and/or fruits; Yellow = Pollen cones; Dark green = Seed cones; Black = Spores (continuation).

N	Specimen identification	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
116	<i>Dicksonia squarrosa</i>												
117	<i>Fagus sylvatica</i>												
118	<i>Pittosporum undulatum</i> 'Variegatum'												
119	<i>Syzygium australe</i>												
120	<i>Halesia carolina</i>												
121	<i>Quercus robur</i>												

4. Discussion

4.1 Value of Markers network

Three years after installation, the base topographic infrastructure has successfully met its initial objectives: providing a stable reference framework for the georeferencing of trees, shrubs, and infrastructure without interfering with routine garden maintenance. Using a total station, the coordinates of trees and shrubs measured from these markers greatly facilitate ongoing and future georeferencing tasks. However, in areas with particularly dense vegetation, the installation of additional reference markers may be necessary to ensure complete coverage. The top design of the markers has proven to be minimally intrusive to visitors. Despite their demonstrated durability, it is recommended that the integrity of the markers be inspected annually to ensure long-term reliability.

4.2 Value of Specimens' data

The collection of data from garden specimens yielded significant insights. Determining tree age and georeferencing their positions enabled the reconstruction of the timeline for the development of specific garden features and helped identify the individuals likely responsible for their planting (Fig. 10).

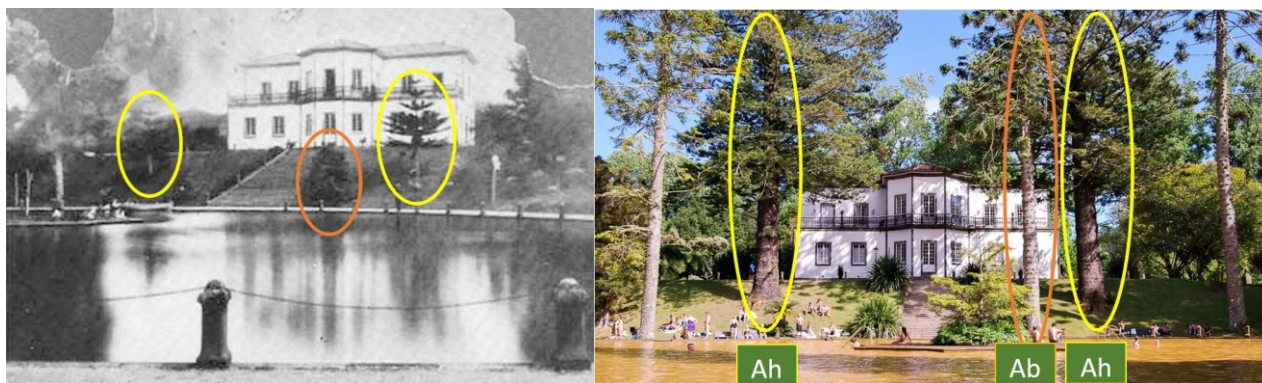


Fig. 10. On the left side: 1900s, Two storey house of Marquis António Borges Medeiros Dias da Câmara e Sousa (1872-1913), with the tank enlarged and the araucarias planted by his father the Viscount Duarte Borges da Câmara Medeiros (1848-1872). On the right side: 2023, 'Botania Hall' (Terra Nostra Garden Hotel) with three documented Araucarias planted by the Viscount. Ab - *Araucaria bidwillii* - specimen 13 alive since 1852 and planted by the Viscount Duarte Borges da Câmara Medeiros [39].

Tree age estimation also provides valuable information on the introduction history of exotic species to the Azores. For example, a report published in 1850 in the magazine 'O Agricultor Micaelense' (The Micaelense Farmer) records that *Araucaria excelsa* (now *Araucaria heterophylla*) was introduced to the Azores by the American Dr. John Webster during his visit to São Miguel Island in 1817. If the specimen planted near the tank of his future father-in-law, Thomas Hickling, is indeed the same tree, it would have been 17 years old at that time, suggesting it was already a substantial specimen.

Age and height measurements have also highlighted new points of interest within the garden. Notably, the oldest tree is a 255-year-old *Quercus robur*, and the tallest is an *Araucaria heterophylla*, reaching 52 m - currently the tallest known specimen in Europe and among the tallest worldwide (table 5). Within the garden, this araucaria also has the largest diameter at breast height (208 cm), while the largest canopy area belongs to a plane tree (*Platanus × hispanica*).

Beyond providing spatial data (UTM points), the collection of morphometric measurements, age estimates, and phenological records generates valuable datasets for environmental scientists, plant physiologists, and biodiversity repositories such as the Global Biodiversity Information Facility (GBIF). Moreover, phenological data enhance the management of the garden's specimens, informing practices such as seed collection and propagation techniques.

Tab. 5. World *Araucaria heterophylla* specimens above 50 m height.

Order	Height (m)	Year	Measurement method:	Place	Reference
1st	55	2019		Private land (Norfolk Island)	Australia National Register of Bigtrees [47]
2nd	52.6	2016	Laser Nikon Forestry 550	Yatton Park (Tauranga, New Zealand)	The New Zealand Tree Register [48]
3rd	52.1	2015	Laser Nikon Forestry 550	Diocesan School for Girls (Auckland, New Zealand)	The New Zealand Tree Register [49]
4th	52	2021	Vertex laser ® VL400 and Total Station	Terra Nostra Garden (São Miguel Island, Azores)	This study (specimen 16)
5th	51.8	2017	Laser Nikon Forestry 550	Yatton Park (Tauranga, New Zealand)	The New Zealand Tree Register [50]
6th	51.8	2003		Tedeschi Winery (Ulupalakua - Maui, Hawaii)	The Gymnosperm Database [51]
7th	50.5	2019	Laser Nikon Forestry 550	Yatton Park (Tauranga, New Zealand)	The New Zealand Tree Register [52]
8th	50.3	2017	Laser Nikon Forestry 550	Fraser Street (Tauranga, New Zealand)	The New Zealand Tree Register [53]
9th	50.1	2010		Margin of Furnas Lake (São Miguel Island Azores)	Açoriano Oriental newspaper [54]
10th	50	2013	Clinometer	Raoul Island (Kermadec Islands, New Zealand)	The New Zealand Tree Register [55]
11th	50	2019	Drone	Private land, Douglas Drive (Norfolk Island)	Australia National Register of Bigtrees [56]

4.3 Combined value of markers network and collected UTM and specimens' data.

The collected UTM coordinates, and specimen data have been integrated into the Terra Nostra Garden database. This dataset, together with future data acquired via the established marker network, forms the foundation of a geographic information system (GIS) capable of generating 3D maps. These include detailed topographical models and three-dimensional representations of individual trees, based on their height, diameter at breast height (DBH), and canopy area.

Furthermore, the UTM data will soon be integrated into the Global Biodiversity Information Facility (GBIF) platform, enriching global biodiversity datasets with precise spatial records of identified specimens.

5. Conclusions

By employing GIS tools, we were able to collect georeferenced data to produce high-precision maps, develop new historical and botanical content, identify previously unrecognized points of interest from a visitor perspective, and pinpoint specimens for conservation and propagation efforts. The proposed walking trails are strategically designed to encompass the maximum number of points of interest, including notable specimens, botanical collections, historical structures, and scenic viewpoints.

In conclusion, this study enhanced both the scientific and economic value of the historic Terra Nostra Garden through the implementation of a GIS framework. The established marker network provides a robust foundation for current and future garden management, supporting network expansion, specimen monitoring, and long-term data compilation and analysis.

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