Annals of Silvicultural Research
47(1), 2022: 30-38
https://journals-crea.4science.it/index.php/asr

Dataset paper

Survival and growth of 711 forest tree taxa in eight French arboretums from three different climate regions

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Received: 30/07/2021 *Accepted: 8/01/2022* *Available online: 14/01/2022*

ABSTRACT Arboretums have been used for decades for scientific, educational, horticultural and aesthetic purposes. Recently, climate change concerns have renewed the interest of the scientific community for these invaluable experimental forest systems. Here, we report a dataset from eight scientific arboretums planted in three contrasted French metropolitan bioclimates: Oceanic, Mountain and Mediterranean. In total, 92,236 trees were planted in 3,678 different plots. Originating from a worldwide range of habitats, from sea-level up to 3,670 m in elevation, the collection spans 711 forest tree taxa (species, subspecies and varieties) from 177 genera. Taxa often include several geographic sources (so-called provenances), often simultaneously in different arboretums, making within species analyses possible. Cool-climate temperate *Pinaceae* (pines, firs, spruces, hemlocks, etc.) are well represented in the Atlantic and Mountain arboretums while Mediterranean arboretums are particularly rich with *genera* from the *Myrtaceae* (mostly eucalypts) and the *Pinaceae* (mostly pines). Data include survival, growth (height and diameter) and health status. Planted between 1969 and 1976, 338 taxa had survived at time of assessment and occurred as at least one individual in one plot. Data can be used to assess species suitability for ecological restoration and afforestation, and to help improve functional niche modeling. Data accessibility: https://data.inrae.fr/dataset.xhtml?persistentId=doi:10.15454/RGMM07.

KEYWORDS: *Myrtaceae, Pinaceae*, adaptation, climate change, common garden, ecological restoration, phenotype.

Introduction

Greenhouse gas emissions have fluctuated widely during the Pleistocene. However, the emission increases of the last decades represent a significant departure from this trend in both magnitude and intensity. Temperatures and precipitations are changing globally, with temperatures currently more than one degree Celsius above pre-industrial levels. Whatever the socio-economic scenario chosen, extreme events such as heat waves, storms and droughts will be on the rise (IPCC 2021). Climate change is affecting and will continue to affect plants, particularly the long-lived trees, in their leaf and flowering phenology, their seed production and natural regeneration, their growth and ultimately, survival (Choat et al. 2018, Walsh et al. 2019).

Anticipating changes and adapting forests to climate change has prompted forest research to explore or revisit the mechanisms involved in phenotypic trait evolution, using new methods, designs and tests, in the hope of broadening management options, for example by creating climate-smart varieties, facilitating local adaptation and guiding assisted migration practice (Fady et al. 2020, Plomion et al. 2016). In this light, common gardens, where among and within species genetic diversity is tested in a common habitat, are powerful tools.

Arboretums are one type of such common gardens, where the genetic factor tested is the species, potentially represented by several different geographic origins.

Arboretums have been used for decades for scientific, educational, horticultural and aesthetic purposes, including for selecting species for afforestation and ecosystem restoration (Dow 1914, Langlet 1971, Fady and Thévenet 2006). Recently, their potential for understanding the effects of environmental change on biological processes and as an experimental system to test for adaptation to extreme events has been renewed, for example as sentinels for biological invasions by assessing natural regeneration and insect outbreaks (Ducatillion et al. 2015, Roques et al. 2015, Kirichenko and Kenis 2016) and for modeling species climate niches by comparing climate data across arboretums in surviving taxa (Vetaas 2002, Vincent et al. 2020).

France holds a wealth of such arboretums on its metropolitan territory, spanning a variety of climates. Particularly, a series of eight arboretums was installed some 50 years ago for testing the ability of a wide range of mostly exotic tree taxa (species, subspecies and varieties) to survive in marginal, stressful habitats (high elevation, low fertility, atmospheric pollution, drought). Surviving and well-growing species were expected to be used to enrich the local tree community or replace local species suffering from die-back. The well-documented, georeferenced survival and growth data from these arboretums we present here, will contribute to the renewed scien-

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 http://dx.doi.org/10.12899/asr-2325

Table 1 - Description of the arboretums. Two arboretums are made of several non-adjacent plots: Basse Seine and Treps. For these two arboretums, data are provided for the entire arboretum, not for each plot.

Arboretum name	Latitude (decimal degree)	Longitude (decimal degree)	Geographic location	District, local name	Region	Climate type	Year of plan-tation	Area (ha)	Elevation (m)	Soil	Average rainfall (mm/yr)	Tempe-rature extremes (°C)	Arboretum structure	Distance between trees at time of plantation (m)
Basse Seine	49.4001	0.9793	Lower Seine valley	Seine-Mari-time, Mare Terreuse	Normandy	Oceanic	1975	15,3	100-140	Silt & flint clay	872	-17 to 38	This is planting site 1 of the arboretum, flat aspect	3 x 2
	49.4186	1.0034	Lower Seine valley	Seine-Ma-ritime, Petit Charme	Normandy	Oceanic	1975	15,3	100-140	Silt & flint clay	872	-17 to 38	This is planting site 2 of the arboretum, flat aspect	3 x 2
	49.4941	1.0576	Lower Seine valley	Seine-Mari-time, Forêt Verte	Normandy	Oceanic	1975	15,3	100-140	Silt & flint clay	872	-17 to 38	This is planting site 3 of the arboretum, flat aspect	3 x 2
Caneiret	43.4968	6.8333	Estérel mountain	Var	Provence	Mediterranean	1973	5	260-320	Rhyolite	932	-12 to 38	Variable aspect across the arboretum (north, south, south-east and a thalweg)	2x1
Ceyreste	43.22966	5.67889	Le Beausset synclinal	Bouches du Rhône	Provence	Mediterranean	1976	2	450-470	Lime-stone, sandstone	691	-10 to 39	Flat aspect and gentle south facing slope	2.5 x 1.3
Col des 3 Sœurs	44.7230	3.5652	Margeride high plateau	Lozère	Massif Central	Mountain	1976	7,5	1390-1480	Granitic sand	1075	-30 to 34	Variable aspects across the arboretum (pass, slope and a ridge	2 x 1
Mourlanchin	43.455861	6.883139	Estérel mountain	Var	Provence	Mediterranean	1971	1	70-140	Rhyolite	847	-12 to 38	North facing slope	2 x 2
Plan Estérel	43.4924	6.8223	Estérel mountain	Var	Provence	Mediterranean	1974	4	410-420	Rhyolite	932	-12 to 38	Flat aspect	2 x 1
Sainte Anastasie	45.2063	2.9776	Cézallier vol-canic plateau	Cantal	Massif Central	Mountain	1969	5,3	1220	Silt	974	-30 to 30	Flat aspect	2 x 2
Treps	43.2625	6.3658	Maures mountain	Var, Treps plateau	Provence	Mediterranean	1975	2	500-600	Gneiss	987	-14 to 38,7	This is planting site 1 of the arboretum, on a plateau, gently facing south	3 x 1.3
	43.2746	6.3810	Maures mountain	Var, Treps thalweg	Provence	Mediterranean	1975	2	500-600	Gneiss	987	-14 to 38,7	This is planting site 2 of the arboretum, in a thalweg	3 x 1.3

tific interest that arboretums represent for understanding how trees adapt to climate change and to providing adaptive solutions to forest management.

Material and methods

Arboretum design and ecological characteristics

All arboretums compare forest tree taxa that are not native to France and use a few autochthonous references to evaluate the potential of this exotic material to survive and grow in regions considered as environmentally stressful. The original choice of taxa in each arboretum based on previous autecological information and dictated by their general potential to survive in cold Mountain, wet Oceanic or dry Mediterranean climates. Final selection was made possible by existing partnerships and availability of plant material (Allemand et al. 1985, Bastien 1988).

The seedlings planted came from seeds collected mostly in natural forests, and more rarely in botanical gardens. The originality of the experimental design is that taxa were often represented by several geographic sources (so-called provenances), often simultaneously in different arboretums. Species, subspecies and varieties were always planted as single-provenance plots. The arboretums are situated in three climatically different French regions: in Normandy under an oceanic climate, in the Massif Central under a cold subalpine climate and in southeastern France (hereafter Provence) under a Mediterranean climate (Fig. 1). The material tested in each of them was selected based on existing empirical knowledge and the ecological and forestry literature at the time, assuming reasonable probability for their survival and growth (Allemand et al. 1985, Bastien 1988). All arboretums were monitored annually or every two years until 1984-1987 and basic silvicultural treatment such as brush clearing to reduce competition and for fire prevention, and fencing against browsing, was applied as needed. Management was performed on occasion until then and more rarely afterwards. The main ecological characteristics of the arboretums and their experimental design are detailed in Table 1 and summarized below.

The Basse Seine, Normandy, arboretum, is composed of three non-adjacent planting sites chosen to represent a typical oak-beech habitat under mild oceanic climate and a trend of increasing air pollution stress from east to west, which has virtually disappeared nowadays, since anti-pollution measures were adopted. Elevation of the three sites is around 100 meters above sea level, and their brown soil is slightly acidic (pH = 4,5) with low water retention capacity. The exotic material planted was believed amenable to environmental pollution and capable of replacing local beech and oak forest in case of marked decline, with the same level of wood production (Bastien 1988). Depending on the species, one to four-year-old bare root or container-grown seedlings, or cuttings from 146 tree species and subspecies (75 conifers and 71 broadleaves) were planted in the springs of 1975 and 1976 after the site was entirely plowed. Seedlings were fertilized and were added a protection against browsing. Following the summer drought of 1976 and up to 1982, seedlings were reintroduced to replace those that had disappeared. Most species and provenances were installed on one or two plots of 20 to 30 seedlings each.

The two arboretums of Massif Central were chosen to sample harsh subalpine climatic conditions, just below the current forest altitudinal limit in the region and where species such as *Pinus sylvestris* L., *Picea abies* (L.) Karst. and *Abies alba* Mill. typically do not perform well or fail in plantation. In both arboretums, one to three-year-old bare root seedlings were planted in plowed lines after a complete removal of the natural vegetation which was left on site and piled between lines. The Sainte-Anastasie arboretum on the Cézallier volcanic plateau, was planted in 1969. At an elevation of 1,220 meters above sea level, its rich and deep silty soil is favorable to tree growth. The 43 species and subspecies (41 conifers and 2 broadleaves) planted there are each represented by a single geographic seed source. The Col des Trois Sœurs arboretum on the Margeride high plateau was planted in 1976. At an elevation of 1,420 meters on average, its soil varies from superficial to deep, originally colonized by either heath or peat. Most of the 77 species and subspecies tested (55 conifers and 22 broadleaves), selected based on the bioclimatic homology of their natural range to that of the arboretum, are each represented by several geographic seed sources. Silvicultural treatment consisted, in 1987, of a thinning and pruning of remaining trees in those plots where minimum height of trees was above 5 meters.

The five Provence arboretums sample typical Mediterranean type climate at low elevation, where summer drought is marked and wild fire risk is high. The exotic material planted included trees and shrubs, chosen based on bioclimatic homology between their natural range and that of the arboretums as well as expert knowledge of their resistance to summer drought, heat waves and late spring frosts (Allemand et al. 1985). Four arboretums (Caneiret, Plan Estérel, Mourlanchin and Treps) were planted between 1971 and 1975 on acidic soil while the fifth one, Ceyreste, was planted in 1976 on limestone. The Treps arboretum is made of two, non-adjacent planting sites. On acidic soil, the native *Pinus pinaster* Aiton forest cover was suffering since the early 1960s from die-back due to the trunk scale insect *Matsucoccus feytaudi*, which was the main motivation for planting the arboretums. In each arboretum, site conditions were very variable, with an exposure from flat to steep, and with superficial to deep soil. Plots were thus made to contain a maximum of 30 trees to reduce within-plot environmental heterogeneity. Potted seedlings were planted during the winter into 60-80 cm deep plowed lines after a complete removal of the natural vegetation which was left on site and piled between lines. Young trees were hoed two years after plantation and the competing vegetation cleared every two years until 1987. The Mourlanchin arboretum was partially destroyed by a forest fire in 1987. Together, the five Provence arboretums test 595 species, subspecies and varieties (89 conifers and 506 broadleaves): 369 taxa are tested in the Caneiret, 69 in Ceyreste, 193 in Mourlanchin, 317 in Plan Estérel, 104 in Treps.

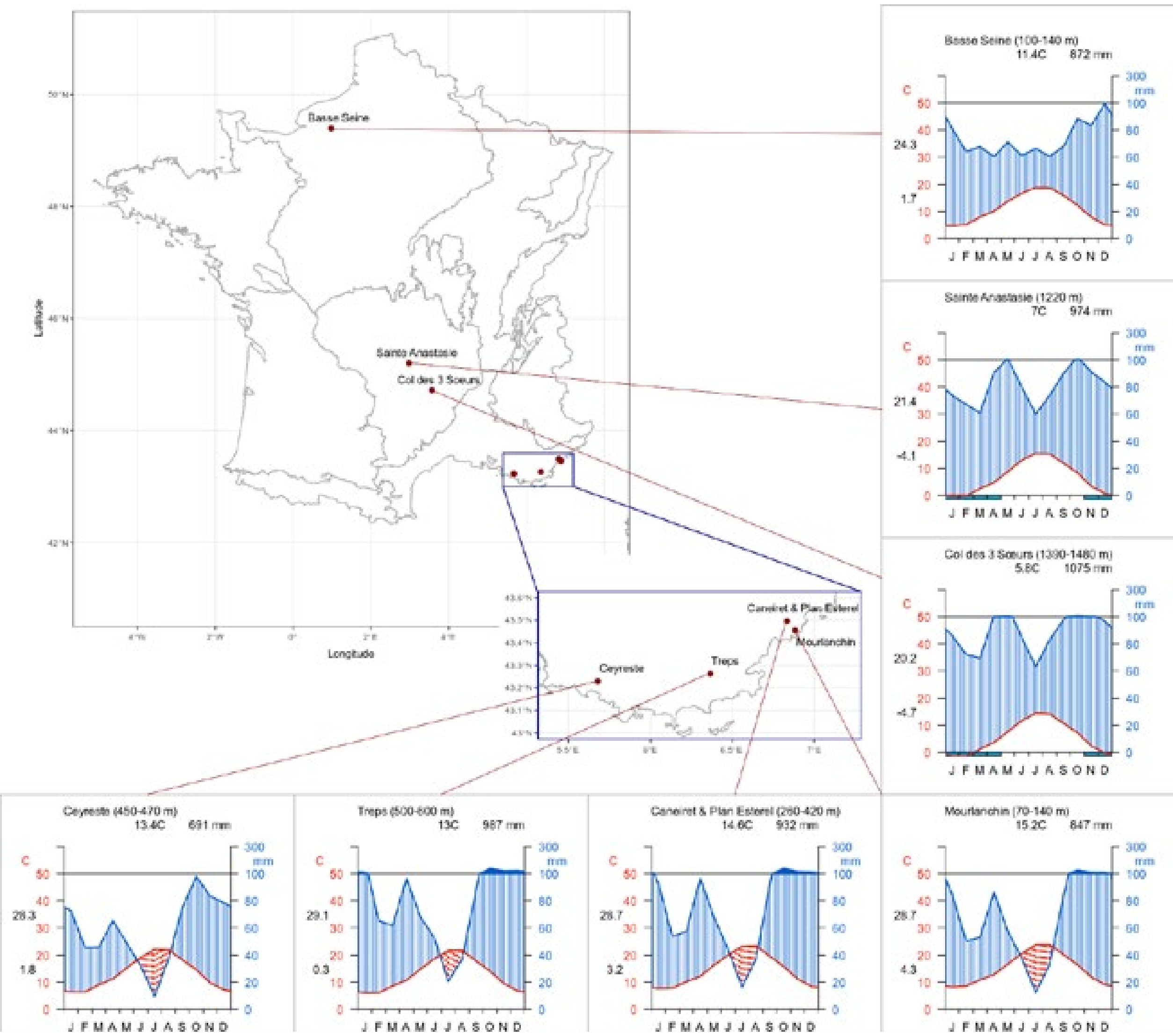
All arboretums are on public land and are managed by the French Forest Service (ONF).

Field monitoring

A first analysis of survival rates after a series of extreme frost and drought events during the late 1970s and early to mid-1980s, provided guidelines on which species and provenances could be used in plantation forests and which should be tested in common gardens (Bastien 1988, Allemand 1989).

In Normandy, survival, height growth and health status data were compiled in 1985 (Bastien 1988) and again in 2012 (Bimont 2012). In Massif Central, survival, height growth and tree form data were compiled in 1987 (Bastien et al. 1990) and again in 1993 (Mons 1993). In Provence, all arboretums were monitored annually until 1984 for survival, total height, diameter at breast height and health status related to frost and drought. Data were compiled and their analysis published by Pestour (1984). Monitoring

Figure 1 - Location of the eight arboretums and their climate diagram according to Walter and Lieth (1960). For each arboretum, the temperature (left vertical axis, red color, degree Celsius) and precipitation (right vertical axis, blue color, millimeters) are shown. Diagram indicates the name of the arboretum, its elevation, its mean annual temperature in degree Celsius (and minimum and maximum mean monthly values on the left) and mean annual precipitation. Drought periods are indicated with red vertical dashed lines. Blue bars below the x-axis show the months with regular frost (when mean monthly minimums are equal to or lower than 0°C). Months with potential frost are not shown. Caneiret and Plan Estérel share the same climate and are shown as a single diagram. Climate data were acquired from the MeteoFrance Aurelhy dataset for the period 1981-2010 (Canellas et al. 2014). Diagrams were computed using the *climatol* package (Guijarro 2019) in R (R Core Team 2021).



was done again in 1987 after two very cold winters (1985 and 1986) and compiled data were published in the form of a list of taxa recommended for plantation forestry and landscaping (Allemand 1989). Naturally regenerated seedlings of planted trees were also monitored as sentinels for early signs of invasiveness in the Estérel mountain arboretums (Caneiret, Plan Estérel and Mourlanchin), a strong preoccupation in the French Riviera (Ducatillion et al. 2015).

The data archives for these past field surveys are not available open-access and are still mostly on paper or available only as aggregated and summarized data. Monitoring was not performed, or very irregularly at best, after 1993, until the period 2011-2015 when a full survey of survival and growth potential was carried out by INRAE and ONF in all arboretums. These are the data we are reporting in this article.

Results

Metadata description

The dataset contains 3,678 entries. Each entry, a row of the dataset, contains data for a single plot per arboretum, and a single taxon. In total, 92,236 trees were planted, originating from a wide range of habitats and elevations, from sea-level up to 3,670 m, and from over 60 countries from all continents except Antarctica (Fig. 2). Together, the arboretums contain 711 forest tree taxa from 177 genera and 63 families (Fig. 3a and 3b.). Out of the 711 taxa, 248 are represented by at least two different geographical origins. Up to 67 taxa share two different bioclimates (Tab. 2) and 318 taxa can be found in at least two different arboretums (Supplementary Table S1, in the online repository: https://data.inrae.fr/dataset.xhtml?persistentId=doi:10.15454/RGMM07). Botanical gardens or arboretums (85 different institutions) were the source of material for 760 entries (from 396 different taxa) out of the 3,678 entries of our database.

Metadata for each plot include the family, genus, species and when relevant, subspecies or variety name initially present in the plot. Botanical names follow the Angiosperm Phylogeny Group (2009). The following resources were used as additional reference: GRIN U.S. National Plant Germplasm System (https://npgsweb.ars-grin.gov), TaxRef for French native plants (https://inpn.mnhn.fr/programme/referentiel-taxonomique-taxref), The Plant List (http://www.theplantlist.org/), Tropicos (http://www.tropicos.org), World Flora Online (http://www.worldfloraonline.org/), African Plant Database (http://www.ville-ge.ch/musinfo/bd/cjb/africa/recherche.php?langue=an) and ABRS Flora of Australia on line (http://www.anbg.gov.au/abrs/online-resources/flora/redirect.jsp).

Figure 2 - World geographic distribution of the forest tree taxa planted in the arboretums.

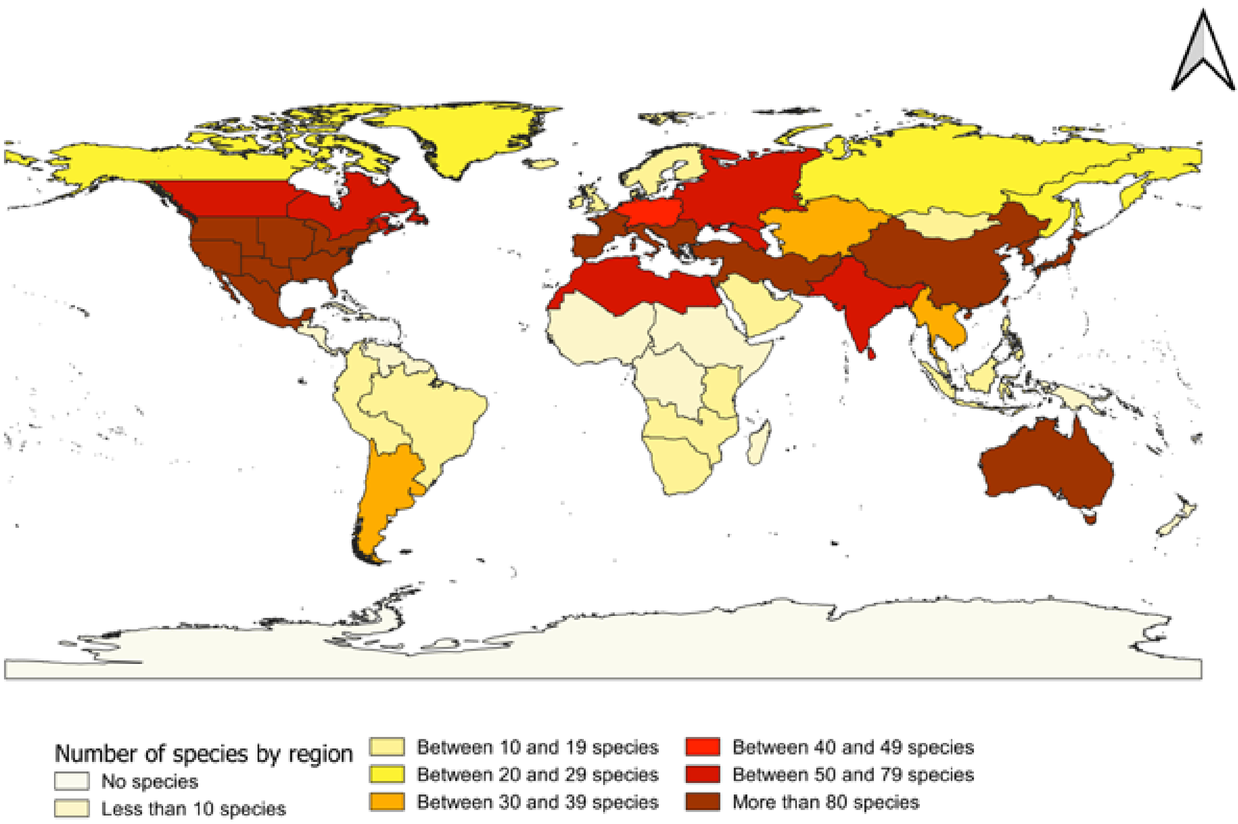


Figure 3 - Number of taxa (in parenthesis) per botanical family (Figure 3a) and genus (Figure 3b) in all arboretums. Families with less than three taxa and genera with less than five taxa were regrouped for clarity. Families *Pinaceae* (7 genera, 115 taxa) and *Myrtaceae* (10 genera, 98 taxa) represent almost 30% of all taxa tested.

Figure 3a

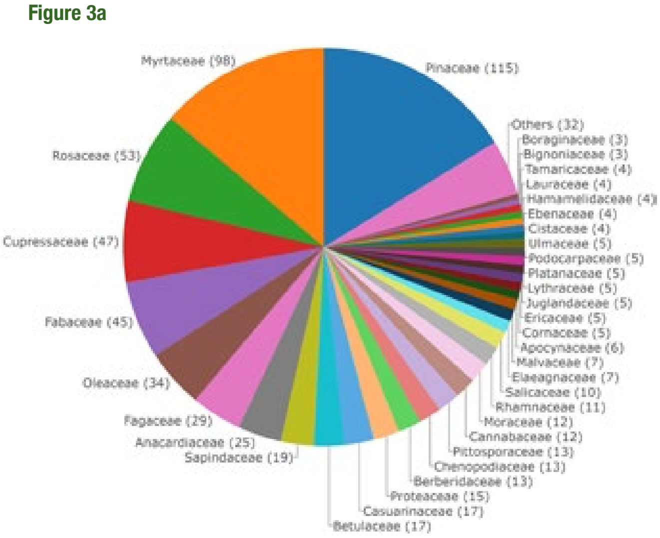


Figure 3b

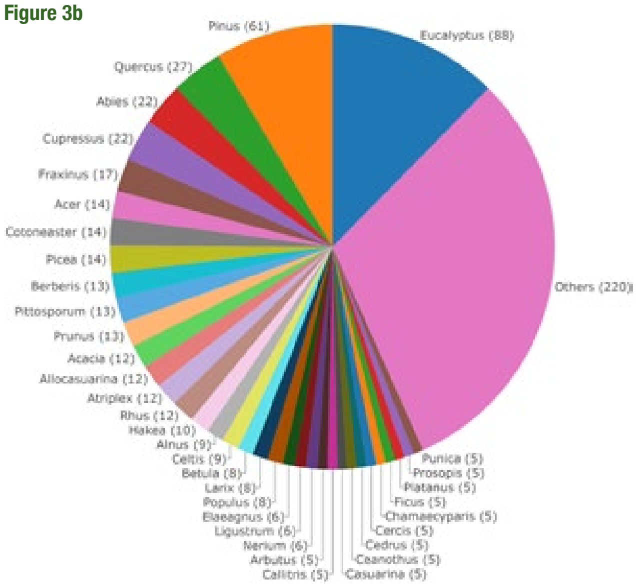


Table 2 - Number of genera and taxa found in each of the three bioclimates experienced by the eight arboretums and shared among bioclimates. Mediterranean is for the Caneiret, Ceyreste, Mourlanchin, Plan Esterel and Treps arboretums, Oceanic is for the Basse Seine arboretums and Subalpine is for the Col des Trois Sœurs and Sainte-Anastasie arboretums.

Bioclimate type	Number of genera planted initially	Number of taxa planted initially	Number of taxa present in 2012
Mediterranean only	125	533	195
Oceanic only	5	47	56
Subalpine only	0	30	21
Mediterranean + Oceanic	43	60	23
Oceanic + Subalpine	17	56	48
All three bioclimate types	13	17	4
Total	177	711	339
4	0.3423	2.1440	

Metadata also include the original genus and species names under which the samples were provided. Their accession number is also listed, along with the main botanic synonyms the taxa may be known to foresters. The countries where the natural distribution area of each taxon is located are listed along with geographic data of the location of origin when available. Geographic information within the arboretum includes the location number of the plot which makes them easy to find on the map of the arboretum. The metadata for facilitating access and reuse of data are described in the file "arboretum_dataset_metadata", available open access in the online repository at the following address: https://data.inrae.fr/dataset.xhtml?persistentId=doi:10.15454/RGMM07. Taxonomic representation per family is indicated in Figure 3.

Data description and access

The data were deposited in the same open access archive as that of the metadata: https://data.inrae.fr/dataset.xhtml?persistentId=doi:10.15454/RGMM07 (see file "arboretum_dataset_data"). Data are also archived on paper at Villa Thuret (INRAE Antibes, France) for Provence arboretums and at UMR BioForA (INRAE and ONF Orléans, France) for Normandy and Massif Central arboretums. These paper archives include maps of the arboretums, student dissertations and correspondence.

Cool-climate temperate conifer of the *Pinaceae* (pines, firs, spruces, hemlocks, etc.) are well represented in the Atlantic and Mountain arboretums while Mediterranean arboretums are particularly rich with *genera* from the *Myrtaceae* (mostly eucalypts) and the *Pinaceae* (mostly pines).

Data include year of plantation, number of seedlings of the same genotype (species or subspecies or variety, and provenance) planted per plot, number of surviving trees per plot at time of evaluation, and, for each plot, health status, dominant height and mean girth at breast height in 2012. Phenotypic and survival assessments provide together 11,013 data points. Survival was evaluated visually. A total of 338 taxa (species and subspecies) have survived (with just one individual in one plot for 24 taxa). Champion survivors include *Acacia cyclops* A. Cunn. ex G. Don, *Arbutus andrachne* L. and *Eucalyptus laevopinea* F.Muell. ex R.T.Baker with 90% survival rate or over in one Mediterranean arboretum each, and *Picea omorika* (Pancic) Purk. with 87% survival rate in the Sainte Anastasie arboretum.

The height of each plot was measured as its dominant height, i.e. the average height of the three tallest trees of the plot. Mean girth at breast height per plot was obtained by averaging the individual measurements carried on all surviving trees. Total height was measured either with a telescopic pole (graduated to the centimeter) or a Vertex dendrometer for trees higher than 7 meters (decimeter precision) and girth was measured either with a flexible tape or a caliper (both graduated to the millimeter). Dominant height was 11.55 meters across all arboretums and ranged from less than 8 meters in Caneiret (Provence) to over 16 meters in Basse Seine (Tab. 3). Mean dominant girth was just below 57 centimeters and ranged from just over 30 cm in Caneiret to over 85 cm in Basse Seine (Tab. 3). Champion growers include *Abies amabilis* (Douglas ex Loudon) J. Forbes in the Basse Seine arboretum with a mean dominant height of almost 25 meters and *Eucalyptus laevopinea* F.Muell. ex R.T.Baker in the Caneiret arboretum with a height of almost 24 meters.

Table 3 - Mean dominant height (in cm) and mean girth (in mm) measured in 2012, for each arboretum. Height measurements were not made in Ceyreste.

Arboretum name	Number of trees planted	Mean age of trees at time of measurement (2012)	Percentage of surviving trees (2012)	Mean dominant height (in cm)	Mean girth (in mm)
Basse Seine	20,186	35	23	1664	851
Caneiret	13,125	38	21	752	303
Ceyreste	2,974	37	20	NA	465
Col des Trois Soeurs	27,166	34	33	938	445
Mourlanchin	6,198	40	10	1146	495
Plan Esterel	11,675	36	18	877	442
Sainte Anastasie	6,371	37	31	1125	560
Treps	4,541	37	25	905	551

Data validation

Survival was evaluated after a careful botanical diagnose to avoid considering naturally regenerated trees in the assessment. As species lists were sometimes incomplete, and when the botanical diagnose could not be performed satisfactorily (for example, as sometimes happened for eucalypts for which no reference herbarium could be used), data were recorded as not available (NA). Dendrometric data acquisition in the field followed strict, high quality standards such as plot-by-plot measurement by the same person to minimize environmental variance for quantitative traits and the use of prefilled electronic data loggers to avoid manual data transfers. Back-to-the-lab, quality checks such as checking differences between current and previous survival values (when available), looking for outliers, etc., were systematically performed independently and aberrant values were removed.

Discussion

Monitoring was not done annually in our study, which is clearly a limitation for matching survival and growth to specific climatic events and for modeling species physiological diversity. However, surviving trees are now half a century old and as the arboretums were never watered, survival data can be used to correlate the pedoclimate of origin and that of the arboretum to assess, at least qualitatively, the climatic niche of each species and its potential for introduction or, conversely, its invasion risk when natural regeneration is present (Primack and Miller-Rushing 2009, Ducatillion et al. 2015).

Using phenotypic trait data (height and diameter) provides an additional way of assessing these potentials and risks, i.e. the functional niche of the species (Benito Garzón et al. 2019). These potentials can be further assessed using tree ring cores. The data can also be used to review if bioclimate homology is a valid criterium for species introduction and acclimation (Conjard 2015). With climate changing globally, these arboretums and others in France and worldwide are a scientific and educational asset that deserves protection and continued management.

Acknowledgements

We acknowledge the invaluable help of dedicated INRAE forest technicians from Avignon, Nancy, Orléans and Pierroton (UEFM, GBFOR, Silva, UEFP) who planted the arboretums and took care of their management during their early stages. We thank Luc Blaison and Tifenn Bouvet (ONF) who greatly contributed to the field data collection.

Funding: The arboretums are part of the INRAE experimental network of forest tree common gardens, GEN4X of the national research infrastructure IN-SYLVA France information system archiving the data, GnpIS (https://urgi.versailles.inra.fr/Tools/GnpIS). Plantation, thinning, pruning and all silvicultural treatments were funded by INRAE and ONF, the French Forest Service. Data acquisition was also funded by INRAE and ONF.

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