## Title: MASTREE+: time-series of plant reproductive effort from six continents

## Running Title: Database of plant reproduction time-series

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## Abstract

Significant gaps remain in understanding the response of plant reproduction to environmental change. This is partly because measuring reproduction in long-lived plants requires direct observation over many years and such datasets have rarely been made publicly available. Here we introduce MASTREE+, a dataset that collates reproductive time-series data from across the globe and makes these data freely available to the community.

MASTREE+ includes 73,828 georeferenced observations of annual reproduction (e.g., seed and fruit counts) in perennial plant populations worldwide. These observations consist of 5,971 population-level time-series from 974 species in 66countries. The mean and median time-series length is 12.4 and 10 years respectively, and the dataset includes 1,122 series that extend over at least two decades (>=20 years of observations). For a subset of well-studied species, MASTREE+ includes extensive replication of time-series across geographical and climatic gradients. Here we describe the open-access dataset, available as a .csv file, and we introduce an associated web-based app for data exploration. MASTREE+ will provide the basis for improved understanding of the response of long-lived plant reproduction to environmental change. Additionally, MASTREE+ will enable investigation of the ecology and evolution of reproductive strategies in perennial plants, and the role of plant reproduction as a driver of ecosystem dynamics.

### Resumen

Aún existen importantes vacíos en la comprensión de la respuesta reproductiva de las plantas al cambio medioambiental, en parte, porque su monitoreo en especies de plantas longevas requiere una observación directa durante muchos años, y estos conjuntos de datos rara vez han estado disponibles. Aquí presentamos a MASTREE +, una base de datos que recopila series de tiempo de la reproducción de las plantas de todo el planeta, poniendo a disposición estos datos de libre acceso para la comunidad científica.

MASTREE + incluye 73.828 puntos de observación de la reproducción anual georreferenciados (ej. conteos de semillas y frutos) en poblaciones de plantas perennes en todo el mundo. Estas observaciones consisten en 5,971 series temporales a nivel de población provenientes de 974 especies en 66 países. La mediana de la duración de las series de tiempo es de 10 años (media = 12.4 años) y el conjunto de datos incluye 1.122 series de al menos dos décadas (>= 20 años de observaciones). Para un subconjunto de especies bien estudiadas, MASTREE + incluye un amplio conjunto de series temporales replicadas en gradientes geográficos y climáticos. Describimos el conjunto de datos de acceso abierto disponible como un archivo .csv y presentamos una aplicación web asociada para la exploración de datos. MASTREE+ proporcionará la base para mejorar la comprensión sobre la respuesta reproductiva de plantas longevas al cambio medioambiental. Además, MASTREE+ facilitará los avances en la investigación de la ecología y la evolución de las estrategias reproductivas en plantas perennes y el papel de la reproducción vegetal como determinante de la dinámica de ecosistemas.

## Keywords

Plant reproduction, masting, flowering, general flowering, demography, regeneration, recruitment

## Introduction

Climate change and other anthropogenic drivers are altering plant demographics, with reported changes in plant mortality, growth, and reproduction (Allen et al. 2010; McDowell et al. 2020; Senf et al. 2018; Pearse, LaMontagne, and Koenig 2017). These demographic shifts are changing the composition and structure of vegetation, with far-reaching effects on ecosystem functioning and services, including complex effects on biodiversity and terrestrial carbon sinks (Ruiz-Benito et al. 2017; Chen et al. 2019; Carnicer et al. 2011; Clark et al. 2016). In most plant species, seed production is a key process limiting sexual reproduction. However, our understanding of climate-driven changes in seed production lags behind other key demographic processes such as growth and mortality (Clark et al. 2021), where inventory data, tree-ring networks and remote sensing have transformed understanding of responses to environmental change (Buras, Rammig, and Zang 2020; Changenet et al. 2021; Klesse et al. 2020). Reproduction and other processes associated with plant recruitment require direct and intensive field-based observation over many years. However, there have been few previous attempts to collate, archive, and make available original data from long-term monitoring studies across taxa and wide geographic areas (Koenig and Knops 2000; Ascoli, Maringer, et al. 2017; Pearse et al. 2020). Consequently, the response of plant reproduction to ongoing environmental change remains poorly understood, and paucity of data compromises the parameterisation of reproduction in models used to predict future vegetation dynamics (Fisher et al. 2018; Vacchiano et al. 2018).

Recent analysis of long-term datasets indicates that seed production may be sensitive to climate change. Where increases in temperature favour reproduction, warming is linked to increased seed production (Buechling et al. 2016; Caignard et al. 2017; Bogdziewicz et al. 2020), whereas in drought-limited populations seed production has declined in association with warming (Redmond, Forcella, and Barger 2012). Additionally, environmental change may alter the interannual variability and spatial synchrony of reproduction (Pearse, LaMontagne, and Koenig 2017; Hacket-Pain and Bogdziewicz 2021). These shifts in reproduction have consequences for recruitment and wider ecosystem dynamics (Pau et al. 2018; Redmond, Forcella, and Barger 2012; Schupp et al. 2019). For example, long-term reductions in tropical rainforest fruit production have been linked with declining vitality of herbivorous megafauna (Bush et al. 2020), and low seed availability can limit forest recovery after large-scale mortality events (Redmond et al. 2018). Beyond changes in mean seed and fruit production, shifts in the spatiotemporal variability of flowering and fruiting (i.e. masting) will also have impacts on key ecosystem services and habitat management (Pearse et al. 2021) including commercial and subsistence food crops (Ladio and Lozada 2004; Calama et al. 2011; Shelef, Weisberg, and Provenza 2017), seed-eating animal population dynamics (Touzot et al. 2020), and human health through the trophic interactions that drive vector-borne zoonotic disease dynamics (Bregnard, Rais, and Voordouw 2020; Bennett et al. 2010). However, the direction and magnitude of reported changes in masting are inconsistent, and this variability in response remains poorly understood (Hacket-Pain and Bogdziewicz 2021).

As the magnitude of plant reproduction is highly variable across time and space (Figure 1), multi-decadal time-series of plant reproductive effort with high replication and sampling across environmental gradients are needed to derive meaningful inferences and predictions from modelling efforts (Vacchiano et al. 2018; Pennekamp et al. 2019; Pearse et al. 2021; Clark et al. 2021). The availability of such data will enable robust estimates of the response of plant reproduction to recent environmental change, and through identification of the underlying drivers, prediction of future trends. MASTREE+ provides these time-series of plant reproductive effort, and will enable testing of changes in masting patterns associated with recent environmental change across multiple species and geographical regions (Pearse, LaMontagne, and Koenig 2017; Hacket-Pain and Bogdziewicz 2021; LaMontagne et al. 2021). Such datasets will also enable new insights into the ecology and evolution of perennial plant reproduction (Dale et al. 2021), and the role of plant reproduction as a driver of other ecological processes including plant recruitment and animal population dynamics (Schupp et al. 2019; Brumme et al. 2021; Curran and Leighton 2000; Connell and Green 2000).

*A picture containing text, plant

Description automatically generated*

**Figure 1**. Examples of population-level time-series of reproductive effort from MASTREE+. For five diverse plant species, data from several local populations are plotted to illustrate the range of spatiotemporal variation in reproduction that is typical in long-lived plants. Note that axis scales and units vary between plots.

## MASTREE+

Here we introduce a project to collate data of perennial plant reproductive time-series. Time-series originate from diverse sources, including 17th century European forestry records of seed production (“mast years”) (Ascoli, Vacchiano, et al. 2017), data from ongoing plant reproductive biology and phenology monitoring programmes (e.g. RENECOFOR, LTER, California Acorn Survey), and projects studying the dynamics of ecosystems including the relationships between seed production and animal demographics (Boutin et al. 2006). Many of these datasets record the number or mass of flowers, seeds, fruits or cones per individual or unit area on a continuous scale. We also include ordinal time-series which record annual reproduction output according to an ordered categorical scale (e.g. failure/partial/full crop) which can be successfully used to investigate the variability and synchrony of plant reproduction (Bogdziewicz et al. 2021).

The current version of MASTREE+ currently includes 5,971 species-specific and georeferenced time-series representing 73,828 annual observations of reproductive effort in perennial plant populations, and the project is designed to continue to assemble and update records (see Section 4 and 5). Mean and median time-series length are 12.6 and 10 years respectively. 2,846 series are based on continuous measures of reproductive effort, and 3,125 are ordinal series. Ordinal series originate mainly from Europe.  Importantly, MASTREE+ contains 1122 time-series ⋝20 years, of which 187 time-series exceed 40 years of observations. Such records will enable quantification of recent changes in plant reproduction, including mean reproductive effort and spatiotemporal variability, and the identification of key drivers of change.

In total, 974 species are represented, drawn from 136 families across the plant Tree of Life. This increases species representation by 168 % compared to the largest previously available compilation (Pearse et al. 2020), which is incorporated into MASTREE+. This expands the potential to quantify reproductive traits that describe the spatiotemporal variability of reproduction (i.e., masting) with other life-history traits to better understand the evolution of plant reproductive strategies (Fernandez-Martinez et al. 2019; Dale et al. 2021; Pesendorfer et al. 2021). For example, we have 67 species overlap with the plant demographic database COMPADRE (Salguero-Gomez et al. 2015), 442 species overlap with seed mass data from the Kew Seed Information Database (Royal Botanic Gardens Kew 2021), and 82 species overlap with the seed germination database SylvanSeeds (Fernandez-Pascual 2021). Reflecting a bias in sampling to temperate forests, woody species from the genera *Quercus* (60 species), *Nothofagus* (10), *Pinus* (25), *Abies* (13), *Acer* (13) and *Eucalyptus* (15) are highly represented, but other well-represented genera include *Acacia* (11), *Shorea* (9) and *Chionochloa* (11).We include data from 66 countries, six continents (Figure 2), and from all the major vegetated biomes (Figure 3). Importantly, we increase data representation from regions that have been unrepresented in previous datasets (Pearse et al. 2020; Ascoli, Maringer, et al. 2017), including south and central America, Africa, and Asia, although these regions remain strongly under-represented.

Sampling intensity varies between species. For example, 71% of species are represented by a single time-series, but other species have high replication, often covering large parts of their geographical distribution. 51 species are represented by at least 10 location-specific time-series. The most replicated species are *Fagus sylvatica* (913 site-specific time-series), *Picea abies* (844), *Pinus sylvestris* (419), *Larix decidua* (395), *Abies alba* (393), *Quercus robur* (188), *Quercus petraea* (161), *Pinus cembra* (135) and *Picea glauca* (108). These and other well-replicated species include data spanning large climatic gradients (Figure 3). These records will enable investigation of intraspecific variation in plant reproduction across climate, space, and time, including trends in the spatiotemporal variability of reproduction. It will also enable comprehensive assessments of intraspecific variability of masting characteristics (i.e. interannual variability, autocorrelation), including variation with environmental conditions that are predicted by theory but have rarely been tested (Pearse et al. 2020; Pesendorfer et al. 2021), and analysis of interspecific variation in spatial synchrony of reproduction (Dale et al. 2021), in functionally diverse plant species.

Map

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**Figure 2**. The geographical distribution of time-series within MASTREE+. The A) spatial and B) latitudinal distribution of species-specific time-series. For B), series are stacked and coloured according to the variable type (Continuous, Ordinal). Plotting of counts for ordinal data in the northern mid-latitudes are truncated due to high sampling intensity in central Europe. Unprojected map, datum = WGS84.

Chart

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**Figure 3**. Distribution of time-series according to local climate (Worldclim v2.1, 30 arcsecond resolution, Mosier, Hill, and Sharp 2014). Only time-series representing reproduction at the stand or patch scale are plotted (regional records are excluded, as local climate data based on coordinates may not be representative). A) Series plotted according to Whittaker biomes (Whittaker 1970), and B) Species with high replication (>=20 species-specific time-series), plotted according to local mean annual temperature. Species are labelled according to the first three characters of the genus followed by the first three characters of the species name, and species are ordered according to the sample site with the lowest mean annual temperature. Unfilled points represent ordinal time-series and filled points represent continuous time-series.

Chart

Description automatically generated **Figure 4.** Timespans covered by species-specific time-series, coloured by data class. Inset plot shows continuous data since 1950 when time-series replication is highest.

## Applications of MASTREE+

MASTREE+ provides the datasets to establish how fecundity, and specifically seed masting, responds to environmental change. It includes the high replication of long time-series required to isolate climate change effects on plant reproductive effort (Mundo, Sanguinetti, and Kitzberger 2021; Hacket-Pain and Bogdziewicz 2021), while high spatial replication across environmental gradients (e.g. Figure 3B) provides the opportunity for a complementary space-for-time substitution approach (Wion et al. 2020). The expected response of masting to climate change remains unresolved, and MASTREE+ will enable testing of contrasting predictions that masting will be unresponsive to trends in mean temperature (Kelly et al. 2013), or will shift predictably based on climate-driven changes in resource limitation (Bogdziewicz 2021). Resolving this uncertainty is a priority because changes in seed masting will impact plant reproductive success, and more widely affect ecosystem services and habitat management (Pearse et al. 2021; Touzot et al. 2020; Ida 2021).

In systems where seed production limits recruitment, MASTREE+ can be utilised to understand the drivers of plant reproduction and regeneration (Abraham et al. 2018; Oliva, Collantes, and Humano 2013; Manríquez et al. 2016). Intraspecific differences in fecundity and masting influence regeneration success, determining species composition and vegetation structure, including during the colonisation of new habitats (Joubert, Smit, and Hoffman 2013), and after natural and anthropogenic disturbance (Martin-DeMoor, Lieffers, and Macdonald 2010; Peters, MacDonald, and Dale 2005; Mokake et al. 2018). Masting characteristics of hundreds of species can be investigated using MASTREE+, and integration with plant trait and demographic databases will enable deeper integration of masting and reproductive strategies within life history theory (Salguero-Gomez et al. 2016). Many ecologically and economically important species show highly variable investment in reproduction between years, and the ability to accurately forecast occasional years of high seed production is a priority for habitat management, with wide ranging applications (Pearse et al. 2021; Chiavetta and Marzini 2021; Pukkala, Hokkanen, and Nikkanen 2010). Predictive models of masting developed and tested using MASTREE+ data may enable more effective seed collection for afforestation and restoration schemes (Kettle et al. 2010; Fargione et al. 2021), inform wildlife and conservation management (Fujiki 2018; Ida 2021; Choquenot and Ruscoe 2000; O'Donnell and Hoare 2012), and enable forecasting of periods of elevated infection risk from tick-borne disease, which predictably follow years of high seed production in many forest ecosystems (Heyman et al. 2012; Cunze et al. 2018; Brugger et al. 2018; Ostfeld, Jones, and Wolff 1996).   
The availability of seed and fruit production datasets in MASTREE+ will be broadly relevant when paired with existing animal population datasets. The pulses of resources associated with large reproductive events are key drivers of the population dynamics of seed-eating insects, mammals, and birds, with cascading impacts through ecosystems (Selonen, Wistbacka, and Korpimaki 2016; Kanamori et al. 2017; Bouchard, Regniere, and Therrien 2018). Time-series in MASTREE+ can be combined with existing long time-series of animal populations and behaviour to identify the drivers of population dynamics, both in seed-dependent species and further down the trophic cascade (Kleef and Wijsman 2015; Lithner and Jönsson 2002). Where species are well replicated in MASTREE+, the spatial synchrony of masting can also be quantified, allowing researchers to determine where regional estimates of masting can be appropriately used as indicators of local variability in seed or fruit availability. The scale of spatial synchrony of masting appears to be highly variable between species (Bogdziewicz et al. 2019), but this has only been quantified of a handful of species so far (LaMontagne et al. 2020; Koenig and Knops 2013).

In masting species, highly variable allocation to reproduction has wider effects on plant resource allocation, and carbon and nutrient cycling through ecosystems, but this remains poorly explored (Muller-Haubold, Hertel, and Leuschner 2015; Brumme et al. 2021; Khanna et al. 2009). Data in MASTREE+ can be combined with existing field and remote-sensing datasets of plant growth or productivity, and with datasets of whole-ecosystem or soil carbon and nutrient fluxes to understand how variable allocation to reproduction influences carbon sequestration above and belowground, and how this varies between species and across environmental gradients (Bajocco et al. 2021; Oddou-Muratorio et al. 2021; Zhang et al. 2022; Nussbaumer et al. 2021). Related work can use MASTREE+ data combined with existing or retrospective sampling (e.g. tree-rings) to address outstanding question regarding resource allocation between growth, reproduction, and defence, particularly how this varies interspecifically and with environmental stress, and how this may shape species and community responses to environmental change (Lauder, Moran, and Hart 2019; Redmond et al. 2019).

## Data sources, acquisition, and compilation

We collected species-specific time-series of annual reproductive effort for terrestrial perennial plant populations, including trees, shrubs, herbs, and grasses. We included data from unmanaged and managed populations, but excluded agricultural crop species subject to selective breeding. Where reproduction was monitored under experimentally manipulated conditions (e.g., fertilisation, warming, rainfall exclusion) we only included data from control plots.

Data were collected for reproductive effort at different stages of the reproductive cycle (e.g., flowers or inflorescences, pollen abundance, number of fruits, cones, or seeds), but 90% of data were mature seed, fruit, or cone production. We did not set a minimum time-series length but prioritised compiling effort on time-series ≥4 years. All time-series represent reproductive effort at the population level, ranging from local populations with <10 individuals to regional estimates of reproduction, and we recorded information on the number of monitored individuals in each population and the spatial scale represented by the time-series (Table 1). We also included information on the original data collection methods, which included litter traps (19.3% of all records), seed, cone, and fruit counts (18.3%), other methods including estimates of cone production using cone or fruit scars and categorical classification of seed and fruit crops by wildlife managers or foresters.

Data were collected from several sources. We harmonised data from previously published compilations of plant reproductive effort displaying differences in data architecture (Pearse et al. 2020; Ascoli, Maringer, et al. 2017; Ascoli et al. 2020). To identify other time-series, we searched Google Scholar and Scopus with multiple combinations of search terms (See Appendix 2). Spanish- and French-language searches was used to increase data representation from South America and Africa. An initial screen was based on the title and abstract to exclude irrelevant sources. Then, potential sources were classified based on the inclusion of useful time-series data of reproductive effort, available as either data tables, figures, descriptions in the text or in supplementary data files, or in online data repositories. Finally, we solicited contributions of previously unpublished datasets from our research networks. Time-series were extracted from the original sources. In the case of values published in tables, in the text, or in online data repositories or supplementary data files, we extracted values directly from the source. In cases where data were contained in figures we used the WebPlotDigitizer tool (Rohatgi 2020). Metadata associated with each time-series was also extracted from the sources, or directly from dataset contributors, and copies of original sources were archived.

### Dataset variables

For each monitored population we recorded annual observations of reproductive effort, the units of measurement, the method used to assess reproductive output and the number of monitored individuals (Table 1). Where multiple measures of reproductive output were recorded for the same population (e.g., where seeds and cones were recorded separately), this was recorded to enable filtering of the dataset for pseudoreplicates (Table 1). For ordinal series, we maintained the original number of classes, but we rescaled to integer scales starting at 1 (lowest reproductive output). For continuous series, where possible we converted data into a common unit (e.g. we converted “seeds/ha” to “seeds/m2”). Years with missing observations are not recorded, and time-series that would otherwise have gaps consist of a set of segments. The *Start* and *End* year corresponds to the first and last observation year for each time-series, respectively, including all segments. *Length* is the number of observations within each time-series, and can therefore be lower than the number of years between the *Start* and *End*. The location (decimal degrees), site name, elevation and country of each time-series were recorded. The spatial scale represented by the time-series was estimated on a four-point scale, from individual stand to region, based on information contained in the original source. Information on the nature of the source, and reference information was also recorded. Full details of data variables are listed in Table 1. Each time-series can be uniquely defined by combining *Alpha\_Number*, *Site\_number*, *Variable\_number* and *Species\_code*.

**Table 1.** Overview of the data variables in the MASTREE+ dataset. A more detailed description of the variables is included in Appendix 5.

|  |  |
| --- | --- |
| **Variable** | **Description** |
| Alpha\_Number | Unique code associated with each original source of data, i.e., the publication, report, or thesis containing extracted data, or the previously unpublished dataset included in MASTREE+ |
| Segment | Temporal segment of a time-series containing gaps (note that years with no observations are not recorded). Individual time-series can consist of multiple segments. |
| Site\_number | Code to differentiate multiple sites from the same original source (Alpha\_Number/Study\_ID) |
| Variable\_number | Code to differentiate multiple measures of reproductive output from the same species-site combination (e.g. where seeds and cones were recorded separately) |
| Year | Year of observation |
| Species | Species identifier, standardised to the The Plant List nomenclature. “spp.” is used to indicate a record identified to the genus level only. “MIXED” indicates a non-species-specific community-level estimate of annual reproductive effort |
| Species\_code | Six-character species identifier |
| Mono\_Poly | Monocarpic (semelparous) or Polycarpic (iteroparous) species |
| Value | The measured value of annual reproductive output |
| VarType | Continuous or Ordinal data. Continuous timeseries are recorded on a continuous scale. Ordinal series are recorded on an ordered categorical scale. All ordinal series are rescaled to start at 1 (lowest reproductive effort) and to contain only integer values |
| Unit | The unit of measurement, where VarType is continuous |
| Max\_Value | The maximum value in a time-series |
| Variable | Categorical classification of the measured variable. Options limited to: cone, flower, fruit, seed, pollen, total reproduction organs. |
| Collection\_method | Classification of the method used to measure reproductive effort. Options are limited to: cone count, cone scar count, flower count, fruit count, fruit scar sound, seed count, seed trap, pollen count, lake sediment pollen count, harvest record, visual crop assessment, other quantification, dendrochronological reconstruction |
| Latitude | Latitude of the record, in decimal degrees |
| Longitude | Longitude of the record, in decimal degrees |
| Coordinate\_flag | A flag to indicate the precision of the latitude and longitude.  A = coordinates provided in the original source  B = coordinates estimated by the compiler based on a map or other location information provided in the original source  C= coordinates estimated by the compiler as the approximate centrepoint of the smallest clearly defined geographical unit provided in the original source (e.g. county, state, island), and potentially of low precision |
| Site | A site name or description, based on information in the original source |
| Country | The country where the observation was recorded |
| Elevation | The elevation of the sample site in metres above sea level, where provided in the original source |
| Spatial\_unit | Categorical classification of spatial scale represented by the record, estimated by the compiler based on information provided in the original source.  stand = <100 ha  patch = 100-10,000 ha  region = 10,000-1,000,000 ha  super-region = >1,000,000 ha |
| No\_individuals | Either the number of monitored individual plants, or the number of litter traps. NA indicates no information in the original source, and 9999 indicates that while the number of monitored individuals was not specified, the source indicated to the compiler that the sample size was likely >=10 individuals or litter traps |
| Start | The first year of observations for the complete time-series, including all segments |
| End | The final year of observations for the complete time-series, including all segments |
| Length | The number of years of observations. Note that may not be equal to the number of years between the Start and End of the time-series, due to gaps in the time-series. |
| Reference | Identification for the original source of the data, see Appendix 4 for the complete list of references |
| Record\_type | Categorisation of the original source.  Peer-reviewed = extracted from peer reviewed literature  Grey = extracted from grey literature  Unpublished = unpublished data |
| ID\_enterer | Identification of the original compiler of the data AHP = Andrew Hacket-Pain; ES = Eliane Schermer; JVM = Jose Moris; XTT = Tingting Xue; TC = Thomas Caignard; DV = Davide Vecchio; DA = Davide Ascoli; IP = Ian Pearse; JL = Jalene LaMontagne; JVD = Joep van Dormolen |
| Date\_entry | Date of data entry into MASTREE+ in the format yyyy-mm-dd |
| Note on data location | Notes on the location of the data within the original source, such as page or figure number |
| Comments | Additional comments |
| Study\_ID | Unique code associated with each source of data. M\_ = series extracted from published literature; A\_ = series incorporated from Ascoli et al. (2017, 2020); PLK\_ = series incorporated from Pearse et al (2017); D\_ = unpublished datasets |

### Technical validation and quality control

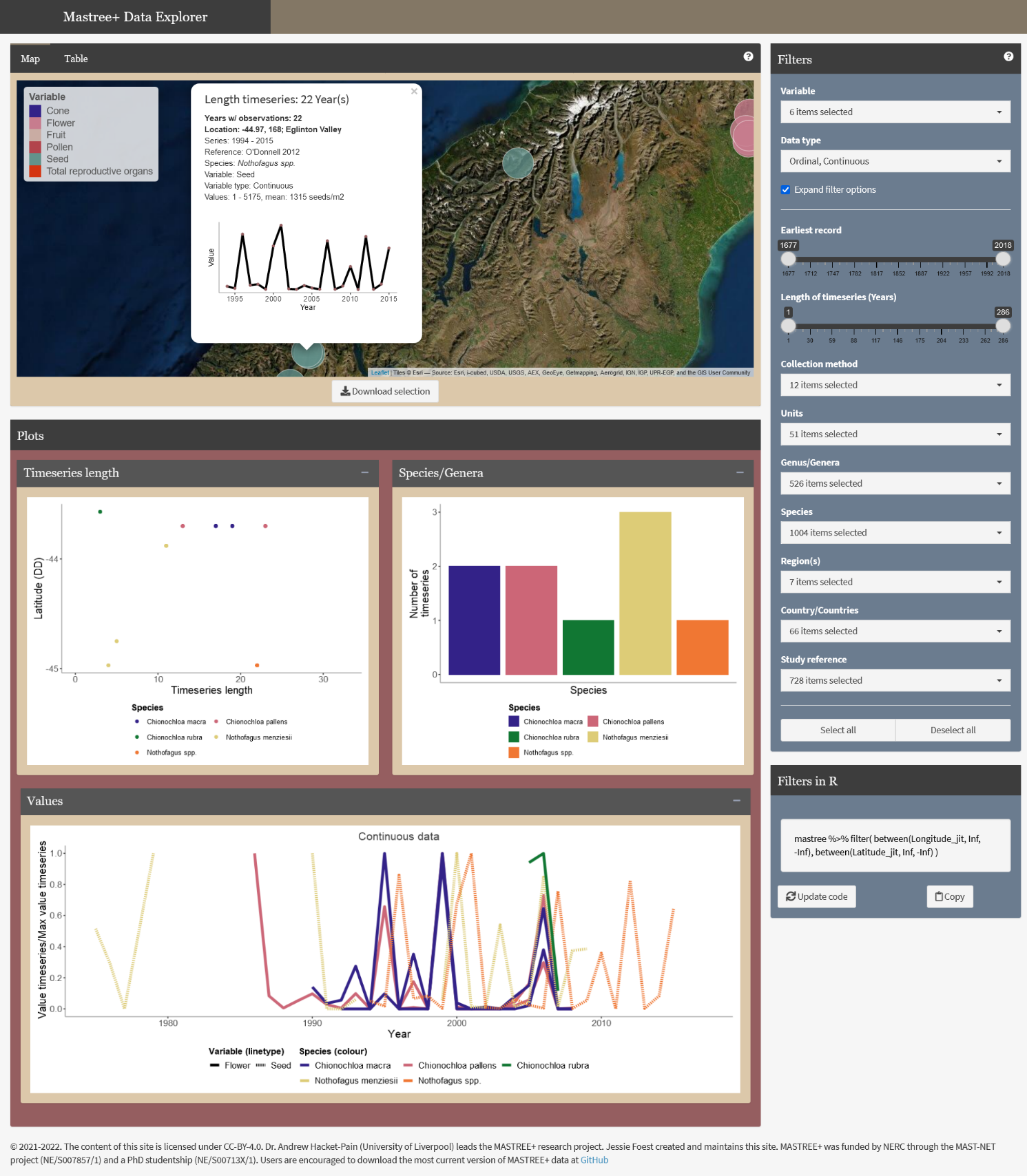
A two-stage approach was adopted to validate time-series data. Initially, we standardised attribute data and checked for errors and inconsistencies within time-series. Species names were checked and standardised to The Plant List nomenclature, using the “Taxonstand” package for R (v. 2.3) (Cayuela et al. 2021). Country names were converted to the English short name (ISO3166-1) using the “countrycode” package for R (v. 1.2.0) (Arel-Bundock, Enevoldsen, and Yetman 2018). Automatic checks were performed to ensure that each time-series was uniquely identified by the identification variables, and that time-series’ observations were uniquely identified by *Year*. *Species\_code* was assigned by automatically combining the first three characters from the TPL-standardised genus and species names. Where separate species shared a *Species\_code*, a unique combination was manually created. The final character of *Species\_code* for populations of a hybrid origin was changed to “X”. We ran various automatic checks to ensure all observations in a time-series had uniform attribute data where such uniformity was expected (i.e., within a time-series, there was only a single value for variables such as *Unit*). Interrelated variables were checked to ensure consistency, for example that time-series spatial data (*Latitude*, *Longitude*) fell within the boundaries of the indicated *Country*. Time-series duration variables (i.e., *Segment, Start, End, Length*) were directly calculated from time-series.

The second stage involved the detection and removal of duplication problems between time-series, i.e., series added multiple times, including with partial overlap, usually when data was published in more than one source. First, we created ‘potential duplication groups’ that contained sets of time-series that shared the same study species and approximate location (using a ± 0.1 decimal degree buffer between pairs of time-series). PDGs containing time-series from multiple sources (*Alpha\_Number*) were then inspected further. Suspect pairs of time-series within PDGs were initially identified based on a correlation test (Spearman's ρ > 0.97), and we then inspected manually for duplication using information including location, units, and collection methods to identify possible duplication. To supplement the semi-automated detection of duplicates, we performed a further manual check, examining groups of time-series that shared the same country and species. Suspect pairs of series might, for example, share matching spatial references, matching site descriptions, and/or matching author names.

Where duplicated series were identified, or where independence could not be confirmed, we selected a single time-series for inclusion in MASTREE+. Generally, the longest time-series was prioritised, unless there were clear signs that a shorter time-series was of higher quality (e.g., the data was directly shared by the author and not extracted from a graph).

## Dataset availability and MASTREE+ Data Explorer

The dataset is provided as a csv file in the online supporting information (Appendix 1), and is distributed under a CC-BY-4.0 licence so that it can be freely used, shared and modified so long as appropriate credit is given.The dataset will be expanded and updated over time, so users are encouraged to check for the latest version of the dataset on GitHub (<https://github.com/JJFoest/MASTREEplus>) and via associated updates to the MASTREE+ Data Explorer. The MASTREE+ Data Explorer allows users to explore the MASTREE+ dataset, and provides an alternative for downloading the dataset, including user-defined subsets thereof. The MASTREE+ Data Explorer was created using the *shiny* package in R (Chang et al. 2021), and can be accessed at <https://mastreeplus.shinyapps.io/mastreeplus/>. Time-series are plotted on a zoomable world map, with updating summary plots showing the time-series lengths and species/genera for the selected region, as well as scaled time-series for initial visualisation of the data within the selected region of interest (Figure 5). Individual time-series can be selected on the map to reveal associated meta-data, including the location, species, and original source. Various filter options allow the user to subset the full dataset. An R script is provided in Appendix 6 that illustrates how to load, manipulate, and visualise the dataset.



**Figure 5.** Example of the MASTREE+ Shiny Data Explorer, showing data from the South Island of New Zealand. The Data Explorer allows the user to explore data availability within MASTREE+, and download the full or user-defined subsets of the dataset.

## Call for data

We have increased taxonomic and geographic representation in MASTREE+, but many gaps remain in the coverage of our dataset. Our goal is to provide a global platform for sharing data on long-lived plant reproduction, and we encourage scientists to submit time-series of annual reproductive effort in perennial plant populations for inclusion in MASTREE+ (Table 2). We will consider all species-specific time-series of four or more years, including continuous and ordinal observations. We include time-series data on flower, seed, fruit, and cone production. which are associated with geographical coordinates. We can include data that represents small local populations through to large regional-scale assessments of reproductive effort. Note that we only record annual reproductive effort. Where data is collected at sub-annual timesteps, this means that reproduction must be aggregated to annual units (e.g., April-March).

Potential contributors of data are encouraged to search the latest version of the dataset to check whether the data is already included in MASTREE+, either by downloading the latest version from GitHub (Section 4) or via the MASTREE+ Data Explorer. If the data are not already included, potential contributors are encouraged to contact the corresponding author to discuss arrangements for sharing data. The minimum data requirements are included in Table 2.

Table 2. Minimum data requirements for submissions to MASTREE+. For further details see Table 1.

|  |
| --- |
| **Minimum data requirements and metadata** |
| Minimum of four consecutive measurements of annual reproductive output |
| Measurement at the population level (local population through regional scale estimates acceptable) |
| Species name according to The Plant List. Records identified to the genus level are acceptable, and measurements of non-species-specific community reproductive effort may be included. |
| Spatial coordinates of the monitored population |
| Details of the method used to measure reproductive effort (e.g., litter traps, seed counts, visual crop estimate, see Table). |

## Data licence

MASTREE+ is published under a CC-BY-4.0 licence, which enables users to copy and redistribute, adapt and modify the dataset in any medium or format and for any purpose, including commercial. You must give appropriate credit by citing this publication, provide a link to the license, and indicate if changes were made (see <https://creativecommons.org/licenses/by/4.0/> for further details). Publications using the RENECOFOR data (Reference = RENECOFOR\_2020) are requested to acknowledge the RENECOFOR network, and send copies of publications to [manuel.nicolas@onf.fr](mailto:manuel.nicolas@onf.fr). Publications using the Lopé data (Reference = Bush\_2021) are requested to cite the original dataset <http://hdl.handle.net/11667/152>), acknowledge The National Parks Agency of Gabon (ANPN) and the University of Stirling, and send copies of any resulting publications to [science@parcsgabon.ga](mailto:science@parcsgabon.ga) and [k.a.abernethy@stir.ac.uk](mailto:k.a.abernethy@stir.ac.uk).

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**Supplementary information files**

Appendix 1: The MASTREE+ dataset as a .csv file

Appendix 2: Literature search for potential sources of masting data

Appendix 3: Data cleaning and removal of duplicated time-series

Appendix 4: Full reference list for sources included MASTREE+

Appendix 5: Extended description of database variables

Appendix 6: Example R script to load, manipulate and visual MASTREE+

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