**Title:** Sylvan Seeds, a database and shiny app to explore the seed germination ecology of the temperate broadleaf and mixed forest biome

**Running title:** Sylvan Seeds, a forest germination database

**Abstract**

*Motivation* Recent discussion on the utility of seed traits in ecology has highlighted the unavailability of reliable germination databases of wide geographical scope. This data paper presents a first global dataset of raw germination data, encompassing an ecologically and biogeographically coherent unit: the Temperate Broadleaf and Mixed Forests biome as defined by the World Wildlife Fund. Data has been gathered using a meta-analytical approach to search the literature.

*Main types of variable contained* Proportion of seeds germinated in different experimental combinations of scarification, stratification, light or darkness, constant or alternating germination temperatures.

*Spatial location and grain* Seed lots collected across the biome and beyond, provided with approximate geographical coordinates in decimal degrees.

*Time period and grain* Seed lots collected between 1920 and today.

*Major taxa and level of measurement* 326 frequent species of the biome, representing 74 families of seed plants (gymnosperms and angiosperms).

*Software format* The database is provided as a single csv file. A shiny web app, Sylvan Seeds, has been written to explore the database and make it accessible to the wide public.

**Keywords:** temperate deciduous forests, temperate evergreen forests, temperate coniferous forests, seed traits, germination database, seed dormancy, germination temperature, alternating temperatures, light germination, dark germination

**Introduction**

Recent discussion on the utility of seed traits in ecology has highlighted the unavailability of reliable germination databases of wide geographical scope (Jiménez-Alfaro, Silveira, Fidelis, Poschlod, & Commander, 2016; Saatkamp et al., 2019). Germination is a complex transition of plant life which is driven by a combination of environmental signals. Amongst these are temperature (Fernández-Pascual, Mattana, & Pritchard, 2019), diurnal temperature alternation (Thompson, Mason, & Grime, 1977), light (Carta, Skourti, Mattana, Vandelook, & Thanos, 2017) and seed dormancy inductors and relievers (Finch-Savage & Leubner-Metzger, 2006). All these signals interact to produce a coarse- and fine-scale regulation of germination timing, integrating inputs from both seasonal climatic cycles (Jurado & Flores, 2005) and local environmental gradients (Fernández-Pascual, Pérez-Arcoiza, Prieto, & Díaz, 2017). The practical consequence of this is that the response of seeds to - for example - light will depend on other conditions set by the experimenter. This makes it difficult to summarise germination “traits” into a single value in a way comparable to seed mass, specific leaf area or plant height (Pérez-Harguindeguy et al., 2013). Another complication of germination “traits” is that they are most frequently reported as a proportion, i.e. a number of seeds germinated out of seeds sown, which implies a set of derived complications in the analytical treatment of the data (Stijnen, Hamza, & Özdemir, 2010). These technical considerations may explain the scarcity of global germination databases. Germination compilations with a biogeographical background, of which the prime example today is the cornerstone book of C. C. Baskin and Baskin (2014), only provide summary information, for instance the interpreted optimal germination temperature instead of the proportion of seeds germinated at this and that temperature.

For this reason, this data paper compiles a first global dataset of raw germination data for an ecologically and biogeographically coherent unit: the Temperate Broadleaf and Mixed Forests biome as defined by the World Wildlife Fund classification of terrestrial ecoregions (Olson et al., 2001). This biome was chosen because it is the home of many of the classical research groups in seed ecology, and therefore it can be expected to provide the widest scope of available data. As a methodology to gather data, a meta-analytical approach (Koricheva, Gurevitch, & Mengersen, 2013) was taken to search the literature for a list of frequent species representing the flora of the biome. The database is made accessible both as the full file and as a shiny web app (Sylvan Seeds) developed to explore the data.

**Methods**

*Species list*

A list of species for which to search germination data was created using vegetation relevés. These relevés were provided by sPlot (Bruelheide et al., 2019), specifically by sPlot’s project #12. They had been recorded in 17 ecoregions of the Temperate Broadleaf and Mixed Forests biome (Appalachian mixed mesophytic forests, Atlantic mixed forests, Cantabrian mixed forests, Caspian Hyrcanian mixed forests, Central Korean deciduous forests, Dinaric Mountains mixed forests, Euxine-Colchic broadleaf forests, Hokkaido deciduous forests, Manchurian mixed forests, Nihonkai evergreen forests, Nihonkai montane deciduous forests, Pindus Mountains mixed forests, Southeastern mixed forests, Taiheiyo evergreen forests, Taiheiyo montane deciduous forests, Western European broadleaf forests, Western Great Lakes forests), plus three neighbouring ecoregions of the Temperate Coniferous Forest biome (Cascade Mountains leeward forests, Central and Southern Cascades forests, Eastern Cascades forests). All relevés came from the Northern Hemisphere and were classified as forest plots by sPlot. The taxa names were standardized to species level with The Plant List (2013) using the ‘Taxonstand’ package (Cayuela, Stein, & Oksanen, 2019) in R version 3.6.2 (R Core Team, 2019). The final vegetation database contained 17,852 relevés and 7,670 standardized species names, considering only seed plants, and encompassing all forest layers. To obtain the final list of species, only species that were present in at least 5% of the relevés of an ecoregion were kept, rendering a list of 1,393 frequent species.

*Web of Science literature search*

The list of frequent species (plus the synonyms recorded in the relevés) was incorporated into a Boolean search string, together with the words "(seed OR seeds) AND (dormancy OR germination)”. This string was searched in the Thompson Reuters Web of Science on 5 Mar 2019, returning 6,791 results. A first filter of the results by the relevance of the title retained 1,490 references, which were accessed to retrieve relevant germination data to build the database. Of these references, 611 provided relevant data, 643 were non-relevant, and for 236 it was impossible to access the full text. The references were considered to contain relevant germination data when they described the results of a laboratory germination experiment in which at least the germination temperature had been controlled and recorded.

*Recording of the database*

For each relevant reference, three blocks of information were recorded. The first block described the plant material, including the species, the populations that had been sampled, the year of sampling (or the year of publication if that information was missing), the country, the geographical coordinates (if not provided in the reference, the closest available toponyms were searched in Google Maps; in some cases the only geographical information was the country, in these cases the coordinates of the capital were recorded). The second block described the experimental conditions: length of the germination incubations, use of stratification (none, cold [< 15ºC], warm [>= 15ºC] or combinations of cold and warm), use of scarification, photoperiod, maximum germination temperature, minimum germination temperature, and weighted average germination temperature. The minority of cases in which GA3 had been applied were excluded. The third block contained the response variable, the final germination proportion: the reported final germination percentages (retrieved from the text, tables or figures) and the reported number of replicates and seeds per replicate were used to calculate a count of seeds sown and a count of seeds germinated.

**Description of the database**

*Summary of contents*

The final database contains 4,814 records (germination proportions for a given seed lot of a species, recorded in a set of experimental conditions) from 611 references. The plant materials had been collected across the Temperate Broadleaf and Mixed Forest biome and beyond (Fig. 1). The oldest record was from 1920 and the top three contributing countries were the USA (1,351), the UK (591) and Japan (525). There were 362 species represented, from 74 seed plant families. The total estimate of seeds used in the experiments was 946,942. The range of germination temperatures (weighted average of the daily thermoperiod) went from -4 to 43ºC, with 2,101 records of constant temperatures and 2,713 of alternating temperatures. Light was used in 2,840 records, darkness in 1,224 and 750 did not provide information on this parameter. The experiments were performed with unstratified seeds in 3,224 records, and of the rest, the majority (1,410) went through cold stratification. Scarification was applied to 252 records.

*Database file*

The database is provided as a csv file, comma separated, named “Supplementary material 1 - Database” (see online supplementary materials). The first row of the file contains the header data, with the following variables: *Species* (The Plant List species names), *Reference* (bibliographic source of the record), *Population* (geographical information of the seed lot), *Year* (year the seed lot was collected), *Country* (country where the seed lot was collected), *Latitude* (approximated latitude where the seed lot was collected, in decimal degrees), *Longitude* (approximated longitude where the seed lot was collected, in decimal degrees), *Scarification* (binary variable indicating whether the seed lot was scarified before the test), *Stratification\_days* (number of days the seed lot was exposed to any type of stratification, before the test), *Stratification\_type* (type of stratification, which can be none, cold, warm or combinations of cold and warm), *Stratification* (binary variable indicating whether the seed lot was stratified or not before the test), *Light* (binary variable indicating whether the seed lot was germinated in light or in darkness), *Photoperiod* (number of hours of light in the daily photoperiod), *Alternating* (binary variable indicating whether the germination test was conducted under constant or alternating temperatures), *Tdif* (difference in degrees between the hottest and the coldest temperatures of the daily thermoperiod), *Tmax* (hottest temperature in the daily thermoperiod), *Tmin* (coldest temperature in the daily thermoperiod), *Tmean* (mean germination temperature, weighted by the length of each phase of the daily thermoperiod), *Temperature* (aggregation of the mean germination temperature in 5 ºC intervals), *Length.experiment* (number of days between the start of the experiment, not including stratification, and the day when germinated seeds were counted), *Germinated* (count of seeds that germinated during the experiment), *Germinable* (count of seeds used in the experiment). Each row below the header represents a record for a seed lot germinated in a given set of experimental conditions.

**Sylvan Seeds app**

To facilitate the visualization of the database, the Sylvan Seeds app was written using the ‘shiny’ package (Chang, Cheng, Allaire, Xie, & Mcpherson, 2020). It is publicly accessible at <http://sylvanseeds.shinyapps.io/sylvanseeds/>. The app uses the ‘tidyverse’ package (Wickham et al., 2019) to aggregate and show results for species and experimental treatments (i.e., aggregating all seed lots of the same species germinated in the same experimental conditions). To facilitate comparisons, germination temperatures are aggregated to 5 ºC intervals. When there is only one seed lot per species and combination of experimental conditions, the binomial 95% confidence interval is calculated using the Wilson method in the ‘binom’ package (Dorai-Raj, 2014). When there is more than one seed lot per species and combination of experimental conditions, the aggregate proportion and binomial confidence intervals are calculated using binomial-normal meta-analysis models (Stijnen et al., 2010) as implemented in the package ‘metaphor’ (Viechtbauer, 2010). By visiting the app, users can consult the available germination information for a species (Fig. 2), the origin of its seed lots, and the bibliographical references for the species.

**Utility of the database**

The database provided in this article, and the web app to visualize it, can have a wide applicability in science and beyond. The data can be used to extend to seed germination the current trend in global analyses of plant traits and functions, both at the species (Díaz et al., 2016) and community levels (Bruelheide et al., 2018). The ecological determinants of seed germination are also valuable information for species distribution models (Bykova, Chuine, Morin, & Higgins, 2012). The visualization of the database with the Sylvan Seeds app can help plant ecologists to select experimental treatments that are adequate for their experiments (Carol C. Baskin, Thompson, & Baskin, 2006). Outside of academia, the data is useful for seed industries (De Vitis et al., 2017), restoration practitioners (Ladouceur et al., 2018) and the implementation of regional schemes for seed-based landscape intervention (Jiménez-Alfaro, Frischie, Stolz, & Gálvez-Ramírez, 2020). The app is accessible to citizens in general who are interested in germinating wild plants. Finally, apart from the dataset itself, this article can bring two innovations to the seed ecology community, helping to advance the agenda of functional seed ecology (Saatkamp et al., 2019). First, the meta-analysis-inspired methodology used to compile the dataset can be extended to other biomes and lists of species, contributing to the creation of a global database for ecologically and biogeographically coherent floras. Second, the database and the app can serve as a standard in further efforts to compile and standardize seed germination data.

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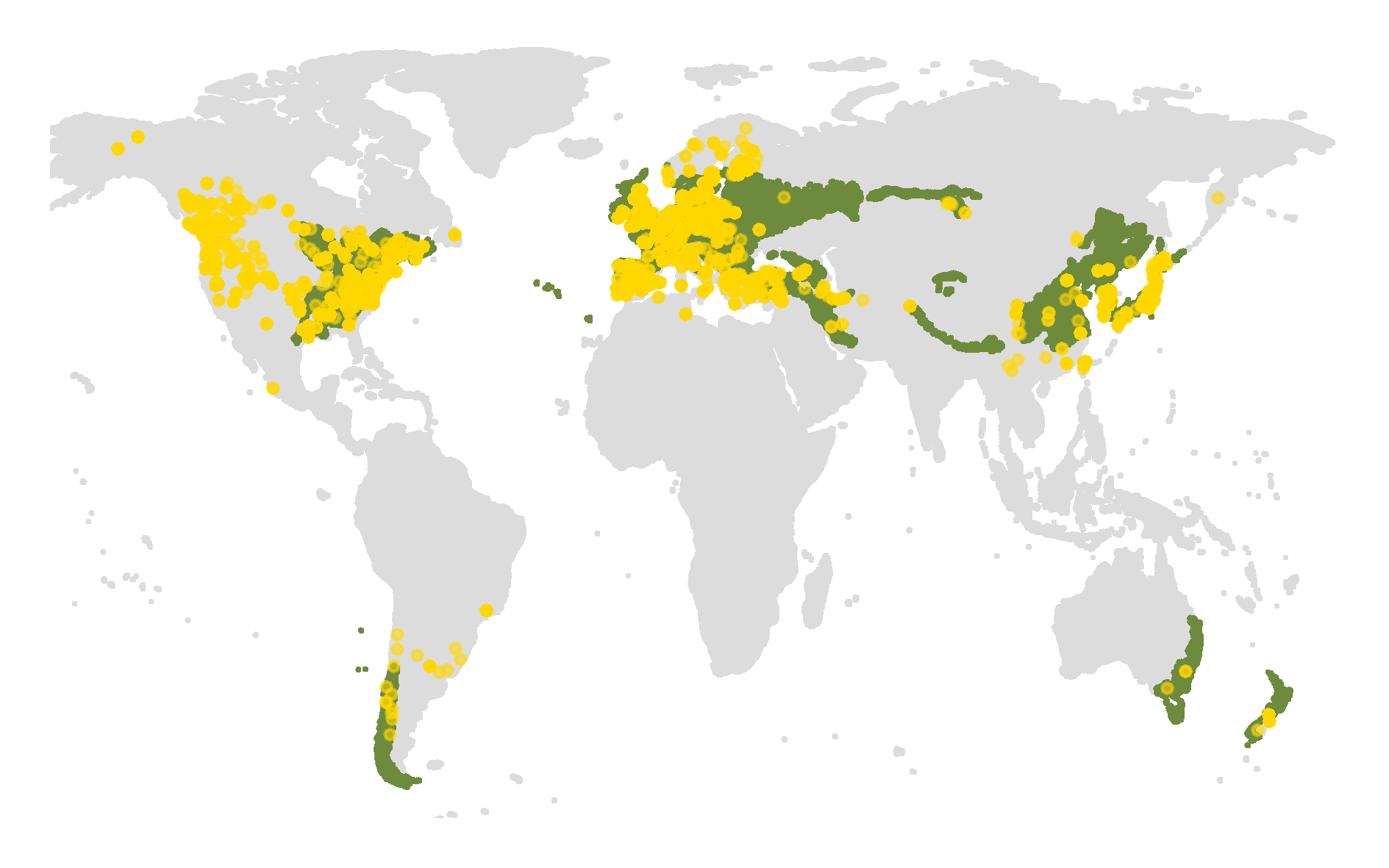
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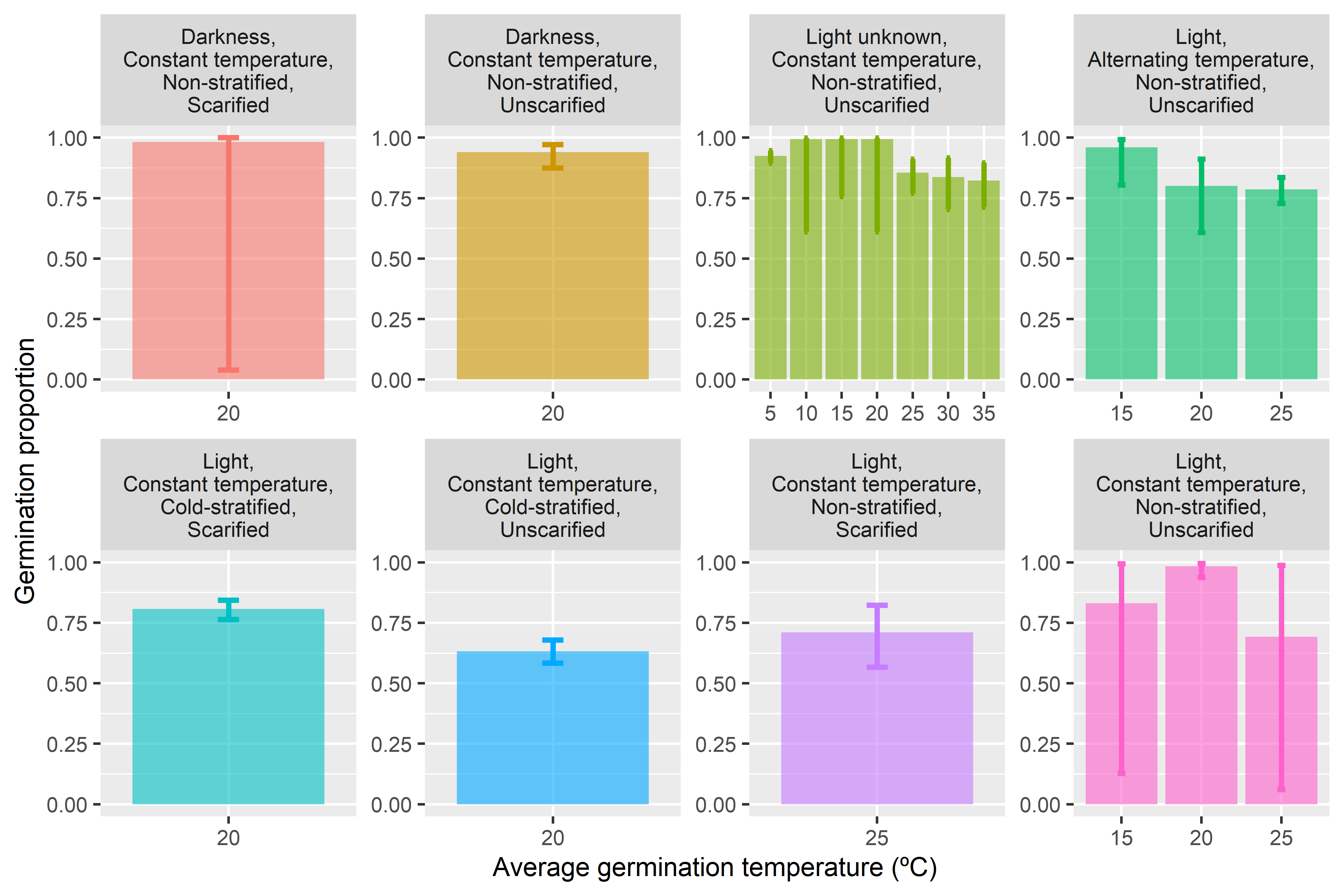
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**Data accessibility statement**

All persons can use the database providing they cite this data paper properly in any publications or in the metadata of any derived products that are produced using the database. The database is provided as supplementary material and will be stored in Dryad. It can be visualized with the Sylvan Seeds app at <http://sylvanseeds.shinyapps.io/sylvanseeds/>. The code of the app is stored at (note: the GitHub page is kept private until publication of the manuscript).



**Figure 1** Geographical distribution of the germination records in the database. Each golden circle is a record. The green areas correspond to the extension of the Temperate Broadleaf and Mixed Forests biome.



**Figure 2** Example of the germination records as shown by the Sylvan Seeds app. Records for one species, the European pedunculate oak, *Quercus robur*. Each panel shows the results for a combination of experimental conditions, with the germination temperature varying within each panel. Bars represent the mean germination proportion and brackets the 95% binomial confidence interval.

**Appendix 1 – Data sources. List of references used to build the germination database.**

*Note: References are provided as they were exported from Web of Science to Endnote, and exactly as they are in the database and the Sylvan Seeds app. They can be edited for final publication.*

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