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

Running Title: Database of plant reproduction time-series

List of Authors

Andrew Hacket-Pain [1] *, Jessie J. Foest [1], Ian S. Pearse [2], Jalene M. LaMontagne [3], Walter D. Koenig [4], Giorgio Vacchiano [5], Michał Bogdziewicz [6,7], Thomas Caignard [8], Paulina Celebias [6], Joep van Dormolen [9], Marcos Fernández-Martínez [10], Jose V. Moris [11], Ciprian Palaghianu [12], Mario Pesendorfer [13], Akiko Satake [14], Eliane Schermer [15], Andrew J. Tanentzap [16], Peter A. Thomas [17], Davide Vecchio [11], Andreas Wion [18], Thomas Wohlgemuth [19], Tingting Xue [20], Katherine Abernethy [21,22], Marcelo Daniel Barrera [23], Jessica H. Barton [3], Stan Boutin [24], Emma R. Bush[25], Sergio Donoso Calderón [26], Felipe S. Carevic[27], Carolina Volkmer de Castilho [28], Juan Manuel Cellini [23], Colin A. Chapman [29,30,31,32], Hazel Chapman [33,34], Francesco Chianucci [35], Patricia da Costa [36], Luc Croisé [37], Andrea Cutini [35], Ben Dantzer [38], R. Justin DeRose [39], Jean Thoussaint Dikangadissi [40], Edmond Dimoto [40], Fernanda Lopes da Fonseca [41], Leonardo Gallo [42], Georg Gratzer [13], David F. Greene [43], Martín A. Hadad [44], Alejandro Huertas Herrera [45,46], K.J. Jeffery [21], Jill F. Johnstone [47], Urs Kalbitzer [48,49], Władysław Kantorowicz [50], Christie A. Klimas [51], Jonathan G.A. Lageard [52], Jeffrey Lane [53], Katharina Lapin [54], Mateusz Ledwon [55], Abigail C. Leeper [3], Maria Vanessa Lencinas [56], Ana Cláudia Lira-Guedes [57], Michael C. Lordon [3], Paula Marchelli [42], Shealyn Marino [58], Harald Schmidt Van Marle [26], Andrew G. McAdam [59], Ludovic R.W. Momont [60], Manuel Nicolas[37], Lúcia Helena de Oliveira Wadt [61], Parisa Panahi [62], Guillermo Martínez Pastur [56], Thomas Patterson [63], Pablo Luis Peri [64], Łukasz Piechnik [65], Mehdi Pourhashemi [66], Claudia Espinoza Quezada [26], Fidel A. Roig [67,68], Karen Peña Rojas [26], Yamina Micaela Rosas [56], Silvio Schueler [54], Barbara Seget [65], Rosina Soler [56], Michael A. Steele [58], Mónica Toro-Manríquez [45,46], Caroline E.G. Tutin [21], Tharcisse Ukizintambara [69], Lee White [21,22,70], Biplang Yadok [34, 71], John L. Willis [72], Anita Zolles [54], Magdalena Żywiec [65], Davide Ascoli [11]

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Andrew Hacket-Pain	andrew.hacket-pain@liverpool.ac.uk	0000-0003-3676-1568
Jessie J. Foest	jessie.foest@liverpool.ac.uk	0000-0002-8236-4646
Ian S. Pearse	ianspearse@gmail.com	
Jalene M. LaMontagne	JLAMONT1@depaul.edu	0000-0001-7713-8591
Walter D. Koenig	wdk4@cornell.edu	0000-0001-6207-1427
Giorgio Vacchiano	giorgio.vacchiano@unimi.it	0000-0001-8100-0659
Michał Bogdziewicz	michalbogdziewicz@gmail.com	0000-0002-6777-9034
Thomas Caignard	tcaignard@gmail.com	
Paulina Celebias	paulina.celebias@gmail.com	0000-0001-9916-2904
Joep van Dormolen	j.van.dormolen@protonmail.com	
Marcos Fernández-Martínez	m.burriach@gmail.com	0000-0002-5661-3610
Jose V. Moris	joseantonio.vazquezmoris@unito.it	0000-0003-0241-7910
Ciprian Palaghianu	palaghianu@gmail.com	0000-0003-2496-2135
Mario Pesendorfer	mario.pesendorfer@yahoo.com	0000-0002-7994-7090
Akiko Satake	akiko.satake@kyudai.jp	0000-0002-0831-8617
Eliane Schermer	eliane.schermer@imbe.fr	0000-0001-7302-2241
Andrew J. Tanentzap	ajt65@cam.ac.uk	
Peter A. Thomas	p.a.thomas@keele.ac.uk	
Davide Vecchio	davide.vecchio@edu.unito.it	
Andreas Wion	andreas.wion@gmail.com	0000-0002-0701-2843
Thomas Wohlgemuth	wohlgemuth@wsl.ch	0000-0002-4623-0894
Tingting Xue	xuetingting1991@outlook.com	
Katherine Abernethy	k.a.abernethy@stir.ac.uk	0000-0002-0393-9342
Marcelo Daniel Barrera	mbarrera@ceres.agro.unlp.edu.ar	
Jessica H. Barton	JBARTO10@depaul.edu	0000-0002-2016-4278
Stan Boutin	sboutin@ualberta.ca	0000-0001-6317-038X
Emma R. Bush	emma.bush.ecology@gmail.com	0000-0003-4036-125X
Sergio Donoso Calderón	sedonoso@uchile.cl	0000-0002-4599-4702
Felipe S. Carevic	felipe_carevic@hotmail.com	0000-0002-6137-2057
Carolina Volkmer de Castilho	carolina.castilho@embrapa.br	
Juan Manuel Cellini	jmc@agro.unlp.edu.ar	0000-0002-7870-5751
Colin A. Chapman	colin.chapman.research@gmail.com	0000-0002-8827-8140
Hazel Chapman	hazel.chapman@canterbury.ac.nz	0000-0001-8509-703X
Francesco Chianucci	andrea.cutini@crea.gov.it	0000-0002-5688-2060
Patricia da Costa	patricia.da-costa@embrapa.br	

Luc Croisé	luc.croise@onf.fr	
Andrea Cutini	andrea.cutini@crea.gov.it	0000-0002-7033-2399
Ben Dantzer	dantzer@umich.edu	0000-0002-3058-265X
R. Justin DeRose	justin.derose@usu.edu	0000-0002-4849-7744
Jean Thoussaint Dikangadissi	scienceparcsgabon@gmail.com	
Edmond Dimoto	SEGC.ED@protonmail.com	
Fernanda Lopes da Fonseca	fernanda.fonseca@embrapa.br	
Leonardo Gallo	gallo.leonardo@inta.gob.ar	
Georg Gratzer	georg.gratzer@boku.ac.at	0000-0002-6355-6562
David F. Greene	david.greene@concordia.ca	
Martín A. Hadad	mhadad@unsj-cuim.edu.ar	0000-0002-9334-064X
Alejandro Huertas Herrera	alejandrohuertasherrera@ulterarius.com	0000-0003-2229-6714
K.J. Jeffery	jefferykath@gmail.com	
Jill F. Johnstone	jfjohnstone@alaska.edu	0000-0001-6131-9339
Urs Kalbitzer	urskalbitzer@gmail.com	0000-0002-6289-7971
Władysław Kantorowicz	W.Kantorowicz@ibles.waw.pl	0000-0002-2474-0113
Christie A. Klimas	CKLIMAS@depaul.edu	0000-0001-9362-1305
Jonathan G.A. Lageard	J.A.Lageard@mmu.ac.uk	0000-0001-8971-0444
Jeffrey Lane	jeffrey.lane@usask.ca	
Katharina Lapin	katharina.lapin@bfw.gv.at	0000-0003-4462-2058
Mateusz Ledwon	ledwon@isez.pan.krakow.pl	0000-0003-3017-6376
Abigail C. Leeper	abigailleeper@gmail.com	
Maria Vanessa Lencinas	mvlencinas@conicet.gov.ar	0000-0002-2123-3976
Ana Cláudia Lira-Guedes	ana-lira.guedes@embrapa.br	0000-0001-9200-4727
Michael C. Lordon	michael.lordon@gmail.com	
Paula Marchelli	marchelli.paula@inta.gob.ar	0000-0002-6949-0656
Shealyn Marino	shealyn.marino@wilkes.edu	
Harald Schmidt Van Marle	hschmid@uchile.cl	
Andrew G. McAdam	Andrew.McAdam@colorado.edu	0000-0001-7323-2572
Ludovic R.W. Momont	lmomont@cyclotis.fr	
Manuel Nicolas	manuel.nicolas@onf.fr	
Lúcia Helena de Oliveira Wadt	lucia.wadt@embrapa.br	
Parisa Panahi	parisapanahi56@yahoo.com	0000-0002-5295-9534
Guillermo Martínez Pastur	gpastur@conicet.gov.ar	0000-0003-2614-5403
Thomas Patterson	Thomas.W.Patterson@usm.edu	0000-0002-3498-893X

Pablo Luis Peri	peri.pablo@inta.gob.ar	0000-0002-5398-4408
Łukasz Piechnik	l.piechnik@botany.pl	0000-0002-3958-7393
Mehdi Pourhashemi	pourhashemi@rifr-ac.ir	0000-0002-8918-6336
Claudia Espinoza Quezada	cespinoza@ug.uchile.cl	
Fidel A. Roig	froig@mendoza-conicet.gob.ar	0000-0003-0987-0486
Karen Peña Rojas	kpena@uchile.cl	
Yamina Micaela Rosas	yamicarosas@gmail.com	0000-0001-7476-399X
Silvio Schueler	silvio.schueler@bfw.gv.at	0000-0003-0155-5692
Barbara Seget	b.seget@botany.pl	0000-0002-7872-926X
Rosina Soler	rosinas@cadic-conicet.gob.ar	0000-0002-5799-1672
Michael A. Steele	michael.steele@wilkes.edu	
Mónica Toro-Manríquez	toro.manriquez.monica@gmail.com	0000-0001-6492-1333
Caroline E.G. Tutin	caroline.tutin@wanadoo.fr	
Tharcisse Ukizintambara	tharcisse.ukizintambara@stonybrook.edu	
Lee White	lwhitemfsepc@gmail.com	
Biplang Yadok	biplang2006@gmail.com	0000-0001-5926-9897
John L. Willis	john.willis@usda.gov	
Anita Zolles	anita.zolles@bfw.gv.at	0000-0003-3476-3172
Magdalena Żywiec	m.zywiec@botany.pl	0000-0002-5992-4051
Davide Ascoli	d.ascoli@unito.it	0000-0002-0546-4467

Institutional affiliations

1. Department of Geography and Planning, School of Environmental Sciences, University of Liverpool, Liverpool, United Kingdom
2. U.S. Geological Survey, Fort Collins Science Center, Fort Collins, Colorado, USA
3. Department of Biological Sciences, DePaul University, Chicago, IL, 60614, USA
4. Hastings Reservation, University of California Berkeley, Carmel Valley CA 93924 USA
5. Department of Agricultural and Environmental Sciences, University of Milan, via Celoria 2, 20133 Milan Italy
6. Institute of Environmental Biology, Faculty of Biology, Adam Mickiewicz University in Poznań, Poland
7. INRAE, LESSEM, University Grenoble Alpes, France
8. Univ. Bordeaux, INRAE, BIOGECO, 33615 Pessac, France

9. Department of Computing, University of London, London, WC1B 5DN, United Kingdom
10. CREAF, Cerdanyola del Vallès, 08193 Barcelona, Catalonia, Spain
11. Department of Agricultural, Forest and Food Sciences (DISAFA), University of Torino, Largo Paolo Braccini 2, 10095, Grugliasco, Torino, Italy
12. Stefan cel Mare Univ Suceava, Forestry Fac, Appl Ecol Lab, Suceava, Romania
13. Institute of Forest Ecology, Department of Forest and Soil Sciences, University of Natural Resources and Life Sciences Vienna, Gregor-Mendel-Strasse 33, A-1180 Vienna, Austria
14. Kyushu University, 819-0395, Fukuoka, Japan
15. Aix Marseille Univ, Avignon Université, CNRS, IRD, IMBE, Marseille, France
16. Ecosystems and Global Change Group, Department of Plant Sciences, University of Cambridge, Cambridge, CB2 3EA, United Kingdom
17. School of Life Sciences, Keele University, Staffordshire ST5 5BG, UK
18. Graduate Degree Program in Ecology and The Department of Forest and Rangeland Stewardship, 1472 Campus Delivery, Colorado State University, Fort Collins, Colorado, 80526, USA
19. Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland
20. College of Civil and Architecture and Engineering, Chuzhou University, China
21. Faculty of Natural Sciences, University of Stirling, Stirling, UK
22. Institut de Recherche en Ecologie Tropicale, CENAREST, Libreville, Gabon
23. Universidad Nacional de la Plata (UNLP). Calle 60 y 118 (1900) La Plata, Buenos Aires, Argentina
24. Department of Biological Sciences, University of Alberta, Edmonton, AB, T6G 2E9, Canada
25. Royal Botanic Garden Edinburgh, Edinburgh, UK
26. Universidad de Chile, Facultad de Ciencias Forestales y de la Conservación de la Naturaleza (FCFCN), La Pintana, 8820808 Santiago, Chile
27. Facultad de Recursos Naturales Renovables, Universidad Arturo Prat, Iquique, Chile.
28. Brazilian Agricultural Research Corporation, Embrapa Roraima, Boa Vista, RR, 69301-970, Brazil
29. Wilson Center,1300 Pennsylvania Avenue NW, Washington, DC 20004,
30. Department of Anthropology, George Washington University, Washington DC, USA
31. School of Life Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa
32. Shaanxi Key Laboratory for Animal Conservation, Northwest University, Xi'an, China
33. School of Biological Sciences, University of Canterbury, New Zealand
34. Nigerian Montane Forest Project, Yelway State, Nigeria
35. CREA - Research Centre for Forestry and Wood, Arezzo, Italy

36. Brazilian Agricultural Research Corporation, Embrapa Meio Ambiente, Jaguariúna, SP, 13918-110, Brazil
37. Office National des Forêts, Département Recherche-Développement-Innovation, Bâtiment B, Boulevard de Constance, 77300 Fontainebleau, France
38. Department of Psychology, Department of Ecology and Evolutionary Biology, University of Michigan, Ann Arbor, MI 48109, USA
39. Department of Wildland Resources and Ecology Center, Utah State University, 5230 Old Main Hill, Logan, UT, 84322-5230, USA
40. Agence Nationale des Parcs Nationaux (ANPN), Libreville, Gabon
41. Brazilian Agricultural Research Corporation, Embrapa Acre, Rio Branco, AC, 69900-970, Brazil
42. Instituto de Investigaciones Forestales y Agropecuarias Bariloche (IFAB) (INTA - CONICET) Instituto Nacional de Tecnología Agropecuaria - Consejo Nacional de Investigaciones Científicas y Técnicas. Modesta Victoria 4450, 8400, Bariloche, Argentina
43. Department of Forestry and Wildland Resources, Humboldt State University, Arcata, CA, 95521, USA
44. Laboratorio de Dendrocronología de Zonas Áridas, CIGEOBIO (CONICET-UNSJ), Av. Ignacio de la Roza 590 (oeste), J5402DCS, Rivadavia, San Juan, Argentina
45. Centro de Investigación en Ecosistemas de la Patagonia (CIEP), Camino Baguales s/n Km 4.7, Coyhaique, Chile
46. Ulterarius Consultores Ambientales y Científicos Ltda, Río de Los Ciervos 5862, Loteo D, km 6 ½ Sur, 6200000 Punta Arenas, Chile
47. University of Alaska Fairbanks, Institute of Arctic Biology, Fairbanks, AK 99775, USA
48. Department for the Ecology of Animal Societies, Max Planck Institute of Animal Behavior, Radolfzell, Germany
49. Department of Biology, University of Konstanz, Konstanz, Germany
50. Department of Silviculture and Genetics of Forest Trees, Forest Research Institute, Raszyn, Poland
51. Environmental Science and Studies Department, DePaul University, McGowan South 203, 1110 West Belden Ave., Chicago, IL 60614, USA
52. Department of Natural Sciences, Manchester Metropolitan University, Manchester M1 5GD, UK
53. Department of Biology, University of Saskatchewan, Saskatoon, SK S7N 5E2, Canada
54. Austrian Research Centre for Forests BFW , Vienna, Austria
55. Institute of Systematics and Evolution of Animals, Polish Academy of Sciences, ul. Sławkowska 17, 31-016 Kraków, Poland

56. Centro Austral de Investigaciones Científicas (CADIC), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET). Houssay 200 (9410) Ushuaia, Tierra del Fuego, Argentina
57. Brazilian Agricultural Research Corporation, Embrapa Amapá, Macapá, AP, 68903-419, Brazil
58. Department of Biology and Institute of the Environment, Wilkes University, Wilkes-Barre PA, USA 18766
59. Department of Ecology and Evolutionary Biology, University of Colorado, Boulder, CO, 80309, USA
60. Independent researcher, Saint-Maur-des-Fossés, France
61. Brazilian Agricultural Research Corporation, Embrapa Rondônia, Porto Velho, RO, 76815-800, Brazil
62. Botany Research Division, Research Institute of Forests and Rangelands, Agricultural Research, Education and Extension Organization, Tehran, Iran
63. School of Biological, Environmental, and Earth Sciences, The University of Southern Mississippi, Hattiesburg, MS, 39406, USA
64. Instituto Nacional de Tecnología Agropecuaria (INTA), Universidad Nacional de la Patagonia Austral (UNPA), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET). cc 332 (9400) Río Gallegos, Santa Cruz, Argentina
65. W. Szafer Institute of Botany, Polish Academy of Sciences, ul. Lubicz 46, 31-512 Kraków, Poland
66. Forest Research Division, Research Institute of Forests and Rangelands, Agricultural Research, Education and Extension Organization, Tehran, Iran
67. Laboratorio de Dendrocronología e Historia Ambiental, IANIGLA - CONICET-Universidad Nacional de Cuyo, Mendoza, Argentina
68. Hémera Centro de Observación de la Tierra, Escuela de Ingeniería Forestal, Facultad de Ciencias, Universidad Mayor, Santiago, Chile
69. Stony Brook University, Long Island, New York
70. Ministère des Eaux, des Forêts, de la Mer, de l'Environnement chargé du Plan Climat, des Objectifs de Development Durable et du Plan d'Affectation des Terres, Boulevard Triomphale, Libreville, Gabon
71. Biosecurity NZ, Ministry for Primary Industries, Wellington 6011, New Zealand
72. USDA Forest Service, Auburn, AL, United States

Contact Information: andrew.hacket-pain@liverpool.ac.uk

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 66 countries. 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

1. 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; I. S. Pearse, LaMontagne, & Koenig, 2017; Senf et al., 2018). 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 (Carnicer et al., 2011; Chen et al., 2019; Clark et al., 2016; Ruiz-Benito et al., 2017). 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, & 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 (Ascoli, Maringer, et al., 2017; Koenig & Knops, 2000; Ian S. Pearse, LaMontagne, Lordon, Hipp, & Koenig, 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 (Bogdziewicz, Kelly, Thomas, Lageard, & Hacket-Pain, 2020; Buechling, Martin, Canham, Shepperd, & Battaglia, 2016; Caignard et al., 2017), whereas in drought-limited populations seed production has declined in association with warming (Redmond, Forcella, & Barger, 2012). Additionally, environmental change may alter the interannual variability and spatial synchrony of reproduction (Hacket-Pain & Bogdziewicz, 2021; I. S. Pearse et al., 2017). These shifts in reproduction have consequences for recruitment and wider ecosystem dynamics (Pau, Okamoto, Calderon, & Wright, 2018; Redmond et al., 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, Weisberg, Cobb, & Clifford, 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 (I.S.

Pearse, Wion, Gonzalez, & Pesendorfer, 2021) including commercial and subsistence food crops (Calama et al., 2011; Ladio & Lozada, 2004; Shelef, Weisberg, & 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 (Bennett et al., 2010; Bregnard, Rais, & Voordouw, 2020). However, the direction and magnitude of reported changes in masting are inconsistent, and this variability in response remains poorly understood (Hacket-Pain & 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 (Clark et al., 2021; I.S. Pearse et al., 2021; Pennekamp et al., 2019; Vacchiano et al., 2018). 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 (Hacket-Pain & Bogdziewicz, 2021; J.M. LaMontagne, Redmond, Greene, & Koenig, 2021; I. S. Pearse et al., 2017). Such datasets will also enable new insights into the ecology and evolution of perennial plant reproduction (Dale, Foest, Hacket-Pain, Bogdziewicz, & Tanentzap, 2021), and the role of plant reproduction as a driver of other ecological processes including plant recruitment and animal population dynamics (Brumme et al., 2021; Connell & Green, 2000; Curran & Leighton, 2000; Schupp et al., 2019).

2. 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, Hacket-Pain, Ascoli, & Szymkowiak, 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 (Ian S. 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 (Dale et al., 2021; Fernandez-Martinez et al., 2019; 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 (Ascoli, Maringer, et al., 2017; Ian S. Pearse et al., 2020), 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 (Ian S. 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.

3. 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 (Hacket-Pain & Bogdziewicz, 2021; Mundo, Sanguinetti, & Kitzberger, 2021), while high spatial replication across environmental gradients (e.g. Figure 3B) provides the opportunity for a complementary space-for-time substitution approach (Wion, Weisberg, Pearse, & Redmond, 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 (Ida, 2021; I.S. Pearse et al., 2021; Touzot et al., 2020).

In systems where seed production limits recruitment, MASTREE+ can be utilised to understand the drivers of plant reproduction and regeneration (Abraham, Sklavou, Loufi, Parissi, & Kyriazopoulos, 2018; Manríquez et al., 2016; Oliva, Collantes, & Humano, 2013). Intraspecific differences in fecundity and masting influence regeneration success, determining species composition and vegetation structure, including during the colonisation of new habitats (Joubert, Smit, & Hoffman, 2013), and after natural and anthropogenic disturbance (Martin-DeMoor, Lieffers, & Macdonald, 2010; Mokake et al., 2018; Peters, MacDonald, & Dale, 2005). 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 (Chiavetta & Marzini, 2021; I.S. Pearse et al., 2021; Pukkala, Hokkanen, & Nikkanen, 2010). Predictive models of masting developed and tested using MASTREE+ data may enable more effective seed collection for afforestation and restoration schemes (Fargione et al., 2021; Kettle et al., 2010), inform wildlife and conservation management (Choquenot & Ruscoe, 2000; Fujiki, 2018; Ida, 2021; O'Donnell & 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 (Brugger, Walter, Chitimia-Dobler, Dobler, & Rubel, 2018; Cunze et al., 2018; Heyman, Thoma, Marié, Cochez, & Essbauer, 2012; Ostfeld, Jones, & 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 (Bouchard, Regniere, & Therrien, 2018; Kanamori, Kuze, Bernard, Malim, & Kohshima, 2017; Selonen, Wistbacka, & Korpimaki, 2016). 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 & Wijsman, 2015; Lithner & 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, Szymkowiak, Fernández-Martínez, Peñuelas, & Espelta, 2019), but this has only been quantified of a handful of species so far (Koenig & Knops, 2013; Jalene M. LaMontagne, Pearse, Greene, & Koenig, 2020).

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 (Brumme et al., 2021; Khanna, Fortmann, Meesenburg, Eichhorn, & Meiwes, 2009; Muller-Haubold, Hertel, & Leuschner, 2015). 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; Nussbaumer et al., 2021; Oddou-Muratorio et al., 2021; Zhang, Wang, Xiao, & Lyu, 2022). 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, & Hart, 2019; Redmond, Davis, Ferrenberg, & Wion, 2019).

4. 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 (Ascoli et al., 2020; Ascoli, Maringer, et al., 2017; Ian S. Pearse 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/m^2"). 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, Macarro, Stein, & Oksanen, 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, & 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 $\rho > 0.97$), 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).

5. 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.

6. 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, Dryad (Section 5) 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

Author contributions

Conceptualisation: Andrew Hacket-Pain, Ian S. Pearse, Walter D. Koenig, Giorgio Vacchiano, Michał Bogdziewicz, Mario Pesendorfer, Akiko Satake, Andrew J. Tanentzap, Peter A. Thomas, Thomas Wohlgemuth, Davide Ascoli

Methodology, including literature search, source classification, data extraction and compilation: Andrew Hacket-Pain, Jessie J. Foest, Ian S. Pearse, Jalene M. LaMontagne, Walter D. Koenig, Giorgio Vacchiano, Michał Bogdziewicz , Thomas Caignard, Paulina Celebias, Joep van Dormolen, Marcos Fernández-Martínez, Jose V. Moris, Ciprian Palaghianu, Mario Pesendorfer, Akiko Satake, Eliane Schermer, Andrew J. Tanentzap, Peter A. Thomas, Davide Vecchio, Andreas Wion, Thomas Wohlgemuth, Tingting Xue, Davide Ascoli

Methodology, including data validation: Andrew Hacket-Pain, Jessie F. Foest

Data Explorer: Jessie J. Foest

Data contribution: Andrew Hacket-Pain, Ian S. Pearse, Jalene M. LaMontagne, Walter D. Koenig, Michał Bogdziewicz, Peter A. Thomas, Katherine Abernethy, Marcelo Daniel Barrera, Jessica H. Barton, Stan Boutin, Emma R. Bush, Sergio Donoso Calderón, Felipe S. Carevic, Carolina Volkmer de Castilho, Juan

Manuel Cellini, Hazel Chapman, Colin A. Chapman, Francesco Chianucci, Patricia da Costa, Luc Croisé, Andrea Cutini, Ben Dantzer, R. Justin DeRose, Jean Thoussaint Dikangadissi, Edmond Dimoto, Fernanda Lopes da Fonseca, Leonardo Gallo, Georg Gratzer, David F. Greene, Martín A. Hadad, Alejandro Huertas Herrera, K.J. Jeffery, Jill F. Johnstone, Urs Kalbitzer, Władysław Kantorowicz, Christie A. Klimas, Jonathan G.A. Lageard, Jeffrey Lane, Katharina Lapin, Mateusz Ledwon, Abigail Leeper, Maria Vanessa Lencinas, Ana Cláudia Lira-Guedes, Michael C. Lordon, Paula Marchelli, Shealyn Marino, Harald Schmidt Van Marle, Andrew G. McAdam, Ludovic R.W. Momont, Manuel Nicolas, Lúcia Helena de Oliveira Wadt, Parisa Panahi, Guillermo Martínez Pastur, Thomas Patterson, Pablo Luis Peri, Łukasz Piechnik, Mehdi Pourhashemi, Claudia Espinoza Quezada, Fidel A. Roig, Karen Peña Rojas, Yamina Micaela Rosas, Silvio Schüler, Barbara Seget, Rosina Soler, Michael A. Steele, Mónica Toro-Manríquez, Caroline E.G. Tutin, Tharcisse Ukizintambara, Lee White, Biplang Yadok, John L. Willis, Anita Zolles, Magdalena Żywiec, Davide Ascoli

Writing – original draft: Andrew Hacket-Pain

Writing – Review and editing: all authors

Supervision and Project administration: Andrew Hacket-Pain

Funding acquisition: Andrew Hacket-Pain, Andrew J. Tanentzap, Peter A. Thomas

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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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Figure Captions

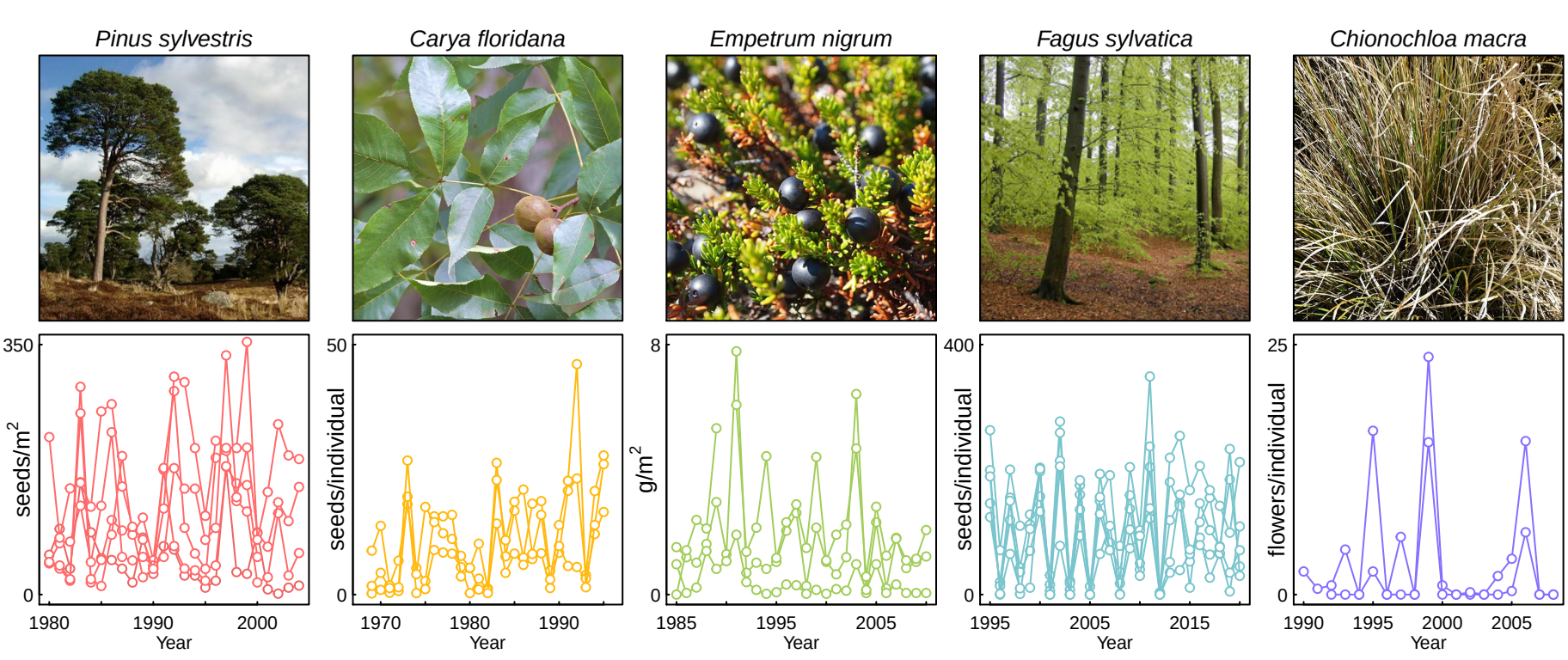
Figure 1. Examples of population-level time-series of reproductive effort from MASTREE+. For five diverse plant species, data from several local populations are plotted to illustrate the range of spatiotemporal variation in reproduction that is typical in long-lived plants. Note that axis scales and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

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.

Figure 3. Distribution of time-series in MASTREE+ according to local climate (Worldclim v2.1, 30 arcsecond resolution, Mosier, Hill, & 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.

Figure 4. Timespans covered by species-specific time-series in MASTREE+, coloured by data class. Inset plot shows continuous data since 1950 when time-series replication is highest.

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.


Pinus sylvestris
Carya floridana
Empetrum nigrum
Fagus sylvatica
Chionochloa macra
seeds/m2
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seeds/individual
flowers/individual
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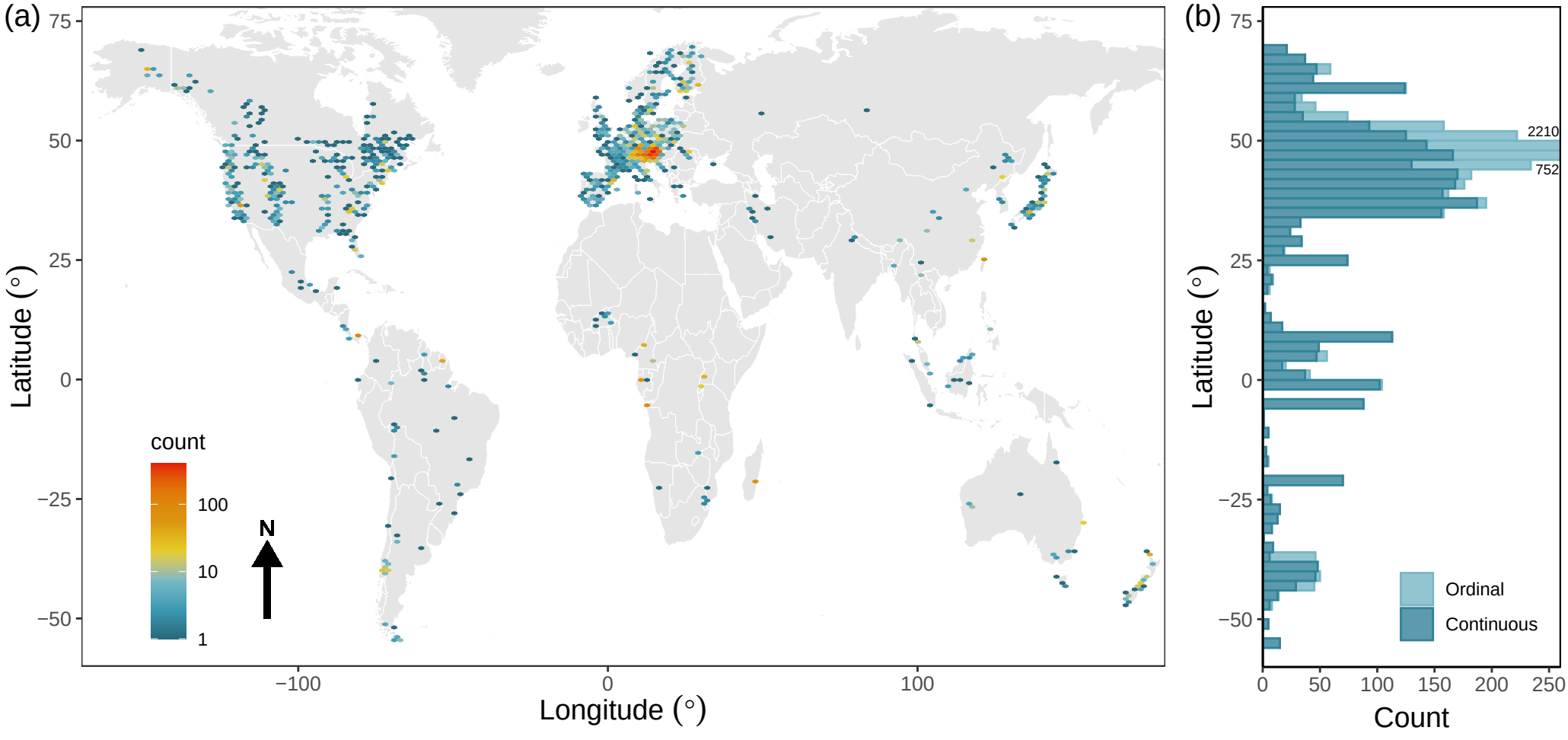
(a)
Latitude (°)
75
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(b)
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2210
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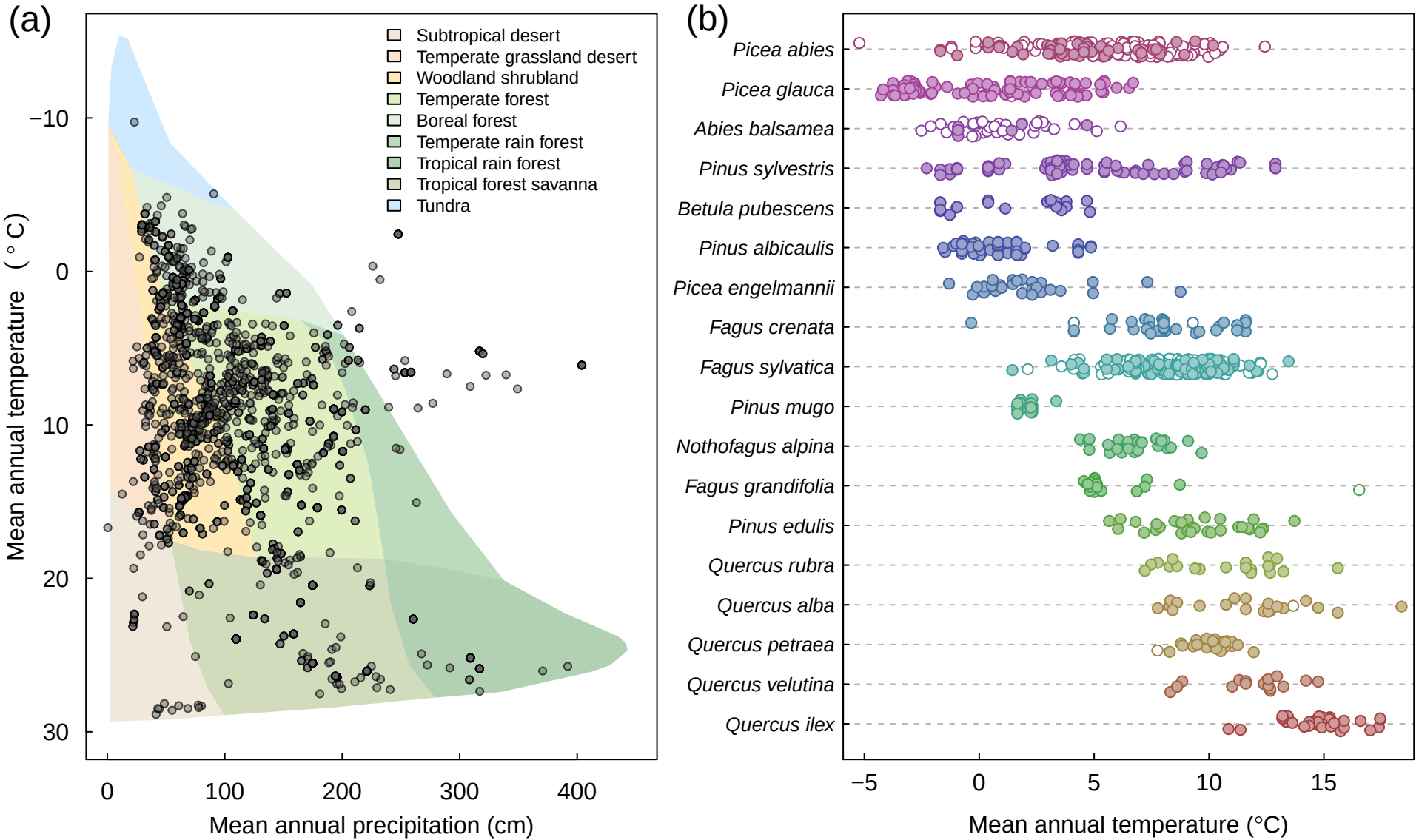
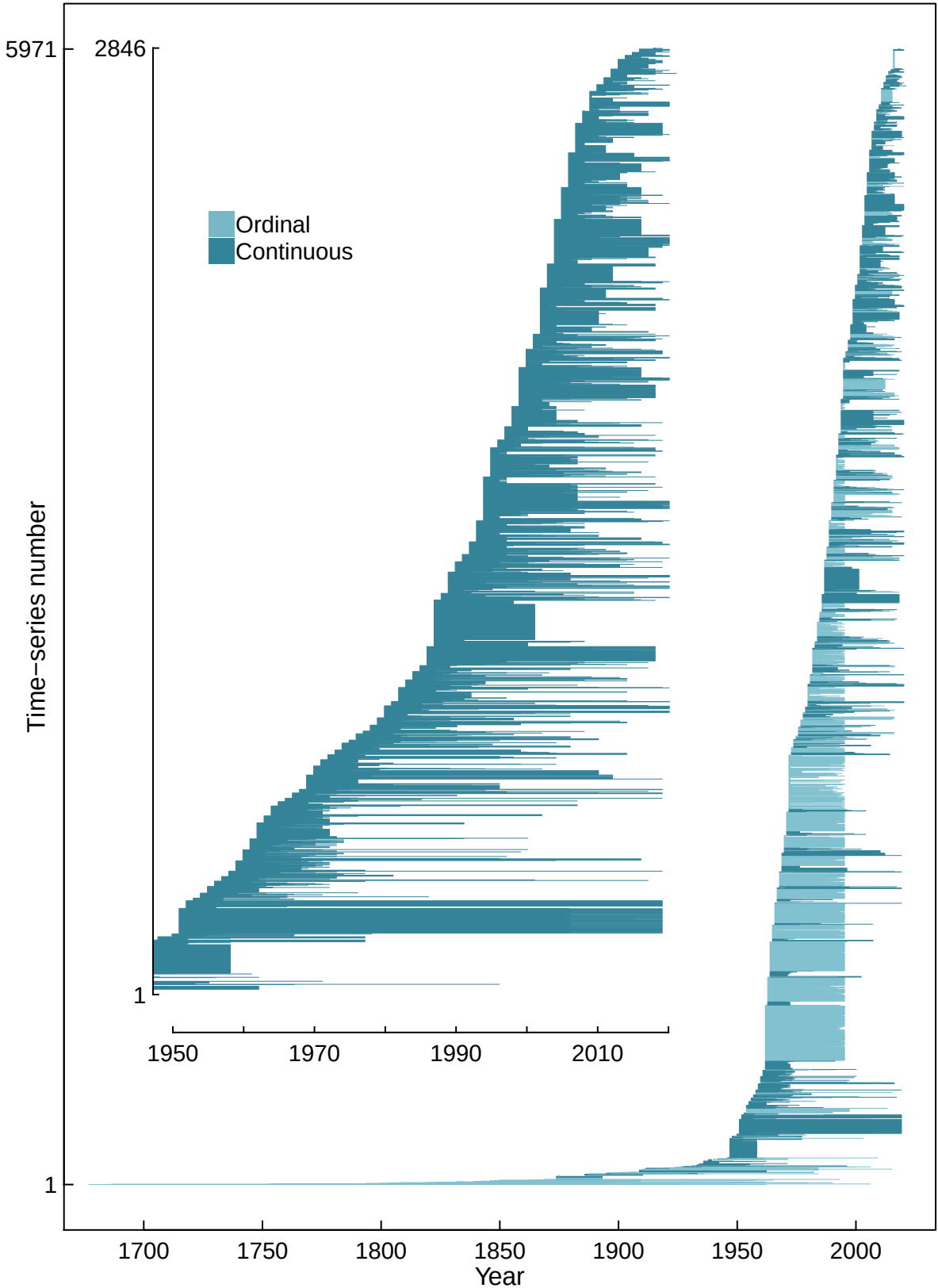
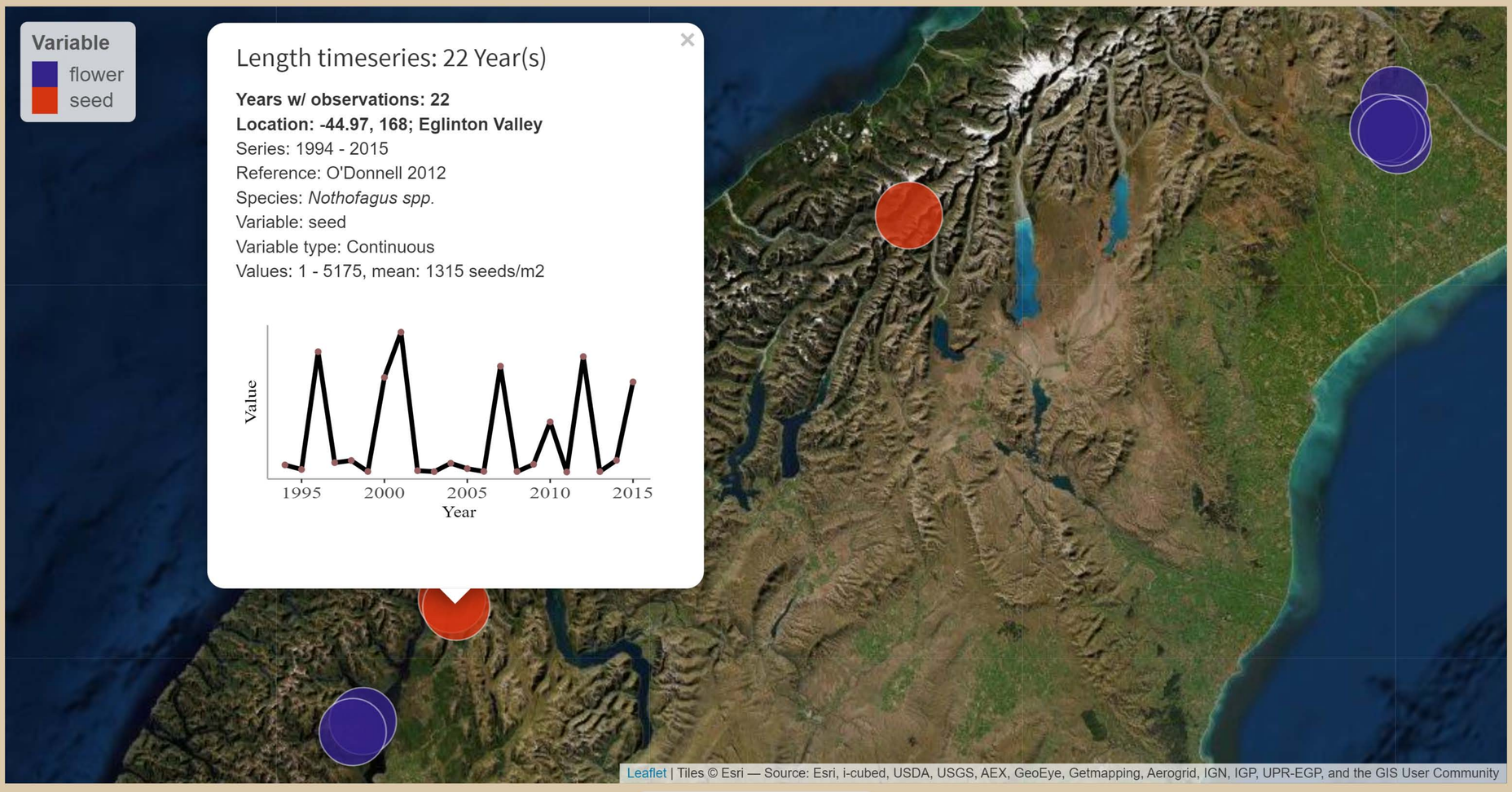

(a)
Subtropical desert
Temperate grassland desert
Woodland shrubland
Temperate forest
Boreal forest
Temperate rain forest
Tropical rain forest
Tropical forest savanna
Tundra
−10
0
10
20
30
Mean annual temperature (°C)
0
100
200
300
400
Mean annual precipitation (cm)
(b)
Picea abies
Picea glauca
Abies balsamea
Pinus sylvestris
Betula pubescens
Pinus albicaulis
Picea engelmannii
Fagus crenata
Fagus sylvatica
Pinus mugo
Nothofagus alpina
Fagus grandifolia
Pinus edulis
Quercus rubra
Quercus alba
Quercus petraea
Quercus velutina
Quercus ilex
−5
0
5
10
15
Mean annual temperature (°C)


5971
2846
1
Ordinal
Continuous
Time−series number
1950
1970
1990
2010
1
1700
1750
1800
1850
1900
1950
2000
Year

Mastree+ Data Explorer

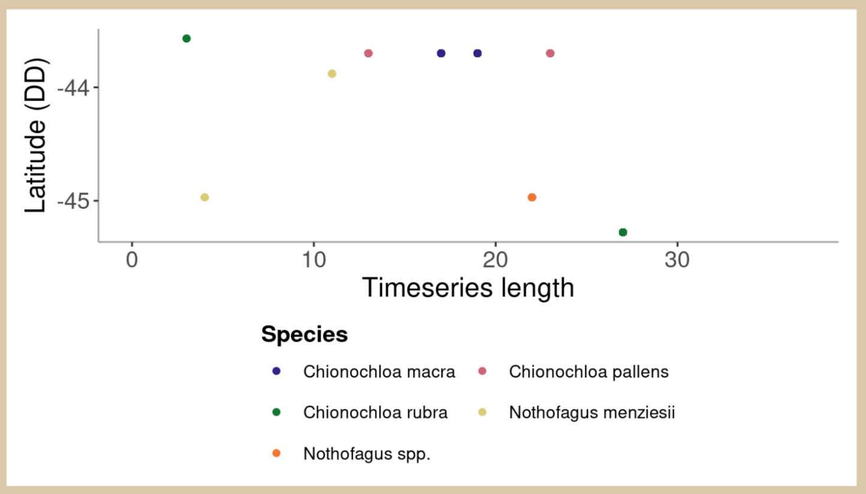
Map | Table



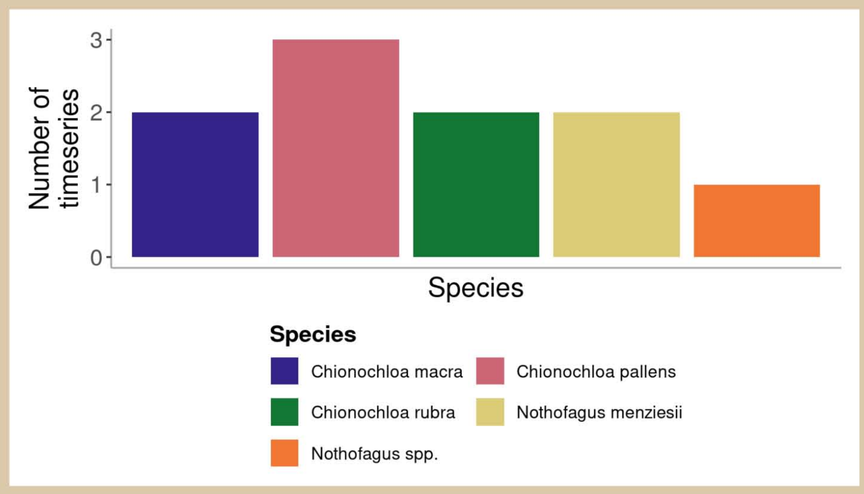
Download selection

Plots

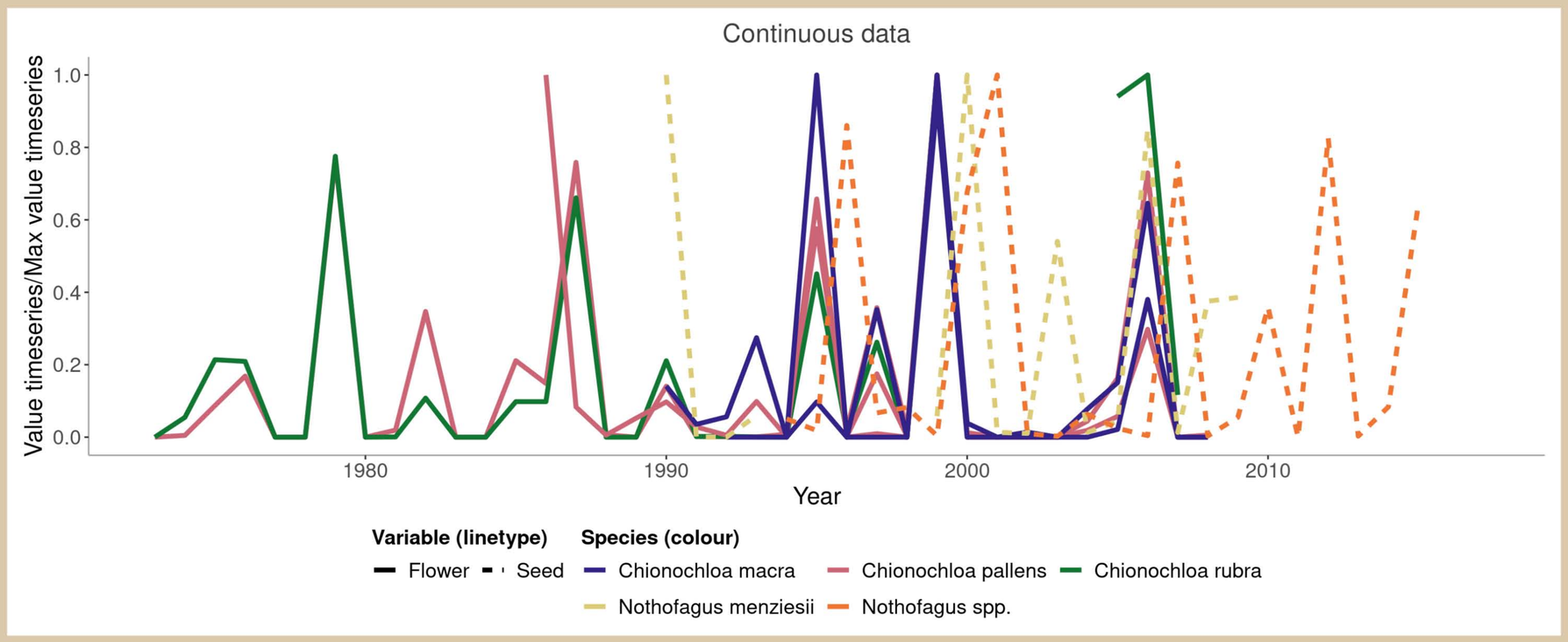
Timeseries length



Species/Genera



Values



Filters

Variable

flower, seed

Data type

Ordinal, Continuous

Expand filter options

Earliest record

1677 — 2018

1677 1712 1747 1782 1817 1852 1887 1922 1957 1992 2018

Length of timeseries (Years)

1 — 286

1 30 59 88 117 146 175 204 233 262 286

Collection method

9 items selected

Units

35 items selected

Genus/Genera

292 items selected

Species

5 items selected

Region(s)

East Asia & Pacific, Latin America & Caribbean

Country/Countries

Argentina, New Zealand

Study reference

12 items selected

Select all | Deselect all

Filters in R

```
mastree %>% filter( between(Longitude, Inf, -Inf), between(Latitude, Inf, -Inf) )
```

Update code | Copy