Oikos

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Robinson, T. M. P., La Pierre, K. J., Vadeboncoeur, M. A., Byrne, K. M., Thomey, M. L. and Colby, S. E. 2013. Seasonal, not annual precipitation drives community productivity across ecosystems. – Oikos 122: 727–738.

Appendix A1

Site-specific details on data collection

Bonanza Creek Experimental Forest (BNZ)

The Bonanza Creek Experimental Forest is a boreal forest study site in the Alaskan interior. The area is dominated by *Picea glauca* and *Populus balsamifera*. Two study communities each were located on floodplain (150 m a.s.l.) and upland (300 m a.s.l) locations. Daily precipitation data were collected from a meteorological station located at the Fairbanks Airport (20 km from the study site). We defined the growing season as 25 May – 24 September (<www.lter.uaf.edu/bnz_climate.cfm>). Each of the four communities was sampled in three plots. Annual readings from ten dendrometer bands per species per 10-cm diameter class and plot inventory data were used to determine annual biomass increment from 1994–2008. ANPP data were from the following data set:

Ruess, R. 2009. Alaska paper birch NPP per tree calculated from dendrometer bands annually from 1994 to 2008, Bonanza Creek LTER – University of Alaska Fairbanks. BNZ: 420, <www.lter.uaf.edu/data_detail.cfm?datafile_pkey=420>

Cedar Creek Ecosystem Science Reserve (CDR)

The Cedar Creek Ecosystem Science Reserve is a 2200 ha area located in central Minnesota. We

used data collected from old-field communities dominated by *Elymus repens*, *Poa pratensis* and *Schizachyrium scoparium*. Daily precipitation data were collected from a meteorological station located at CDR. We defined the growing season as 25 April – 15 October each year (Dan Bahauddin, pers. comm.).

ANPP was harvested from 1982–2006 from control plots of the long-term nitrogen deposition experiment at CDR. The 46 16-m^2 control plots were located in four old fields (A, B, C, and D; n = 12 per field, except field D where n = 10). ANPP was harvested by clipping all biomass 1–2 cm above ground level within a 0.3-m^2 quadrat of each plot at peak biomass. The quadrat sampled was relocated yearly to prevent a sampling effect. Collected biomass was separated by species, dried at 60ºC for 48 h, and weighed. Precipitation and ANPP data were from the following data sets:

Tilman, D. 2008. Experiment 001 - Aboveground biomass data. St. Paul, MN: Cedar Creek Ecosystem Science Reserve Data Base: E001. [Database]. <www.cedarcreek.umn.edu/research/data/data.php?input=ple001>

Seeley, M. 2010. Experiment 080 – Meterologic measurements at Cedar Creek Natural History Area. St. Paul, MN: Cedar Creek Ecosystem Science Reserve Data Base: E080. [Database]. <www.cedarcreek.umn.edu/research/data/data.php?input=clime080>

Capulin Volcano National Monument (CVO)

Capulin Volcano National Monument was selected randomly from piñion *Pinus edulis* woodland sites with modern tree-ring data hosted by the NOAA paleoclimatology database <www.ncdc.noaa.gov/paleo/treering.html>. The site is located in northeastern New Mexico. Daily precipitation data are from Des Moines, NM (12 km east of the study site). We defined the growing season as 15 April – 15 October (Baker 1944).

Tree ring measurements of 23 individual *P. edulus* collected from 1951–1991 were used to determine mean annual production per tree by 1) linear detrending, 2) normalization of

residuals to each tree's mean increment width, and 3) calculation of an unweighted mean increment width for each year across all cores with complete data for the study period. The resulting dimensionless values serve as an index of production, but cannot be scaled to ANPP in g m^{-2} y^{-1}.

Baker F.S. 1944. Mountain climates of the western United States. – Ecol. Monogr. 14: 223–254.

ANPP data were from the following data set:

Woodhouse, C. A. and Brown, P. M. 1998. Capulin Volcano - PIED - ITRDB NM576. [Database] <http://hurricane.ncdc.noaa.gov/pls/paleox/f?p=519:1:2874077818569153::::P1_STUDY_ID:5287>

Coweeta Hydrologic Laboratory (CWT)

Coweeta Hydrologic Laboratory has a mixed deciduous forest in the mountains of southwestern North Carolina. Five distinct community types are sampled along an elevation gradient: oak pine, cove hardwoods, mixed oak lowland, mixed oak highland, northern hardwoods. The oak pine community is characterized by *Pinus rigida*, *Quercus* spp. and *Carya* spp. The cove hardwoods are dominated by *Liriodendron tulipifera*, *Quercus prinus* and *Carya* spp. The mixed oak lowlands and uplands are characterized by *Quercus* spp., *Carya* spp. and *Rhododendron maximum*. The northern hardwoods are dominated by *Betula* spp., *Tilia heterophylla* and *Quercus rubra*. Daily precipitation data were collected from raingauge 6 at CWT. We defined the growing season as 15 April – 24 October (Hwang et al. 2011).

Deciduous species' litterfall collected annually in ten 0.85 m^2 baskets was used as an index of foliar production at each of the five 20 × 40 m plots. Although species composition varies across the gradient, values should be comparable within each community type.

Hwang, T. C. et al. 2011. Topography-mediated controls on local vegetation phenology estimated from MODIS vegetation index. – Landscape Ecol. 26: 541–556.

ANPP data were from the following data set:

Knoepp, J., Clark, J., Vose, J., Haines, B. and Crossley, D. A. Terrestrial gradient leaf litter weights. Athens, GA: Coweeta Hydrologic Laboratory Database: 1121 [Database]. <http://coweeta.uga.edu/summaries/summary1121_b.html>

Harvard Forest (HFR)

Harvard Forest is a 1214 ha hardwood-hemlock-pine forest located in central Massachusetts. The area is dominated by both deciduous and evergreen species, including *Tsuga canadensis*, *Betula lenta*, *Acer rubrum*, *Quercus rubra* and *Pinus strobus*. Daily precipitation data were collected from meteorological stations on-site; missing data (from 1994 and 1995) were filled using NCDC data from Tully Lake in Athol (13 km NNW of the study site). We defined the growing season as 25 April – 24September (Richardson et al. 2006). ANPP data were collected as foliar litterfall from deciduous species from 1998–2007 from 34 plots located in the footprint of an HFR flux tower ('EMS litter'). Additionally, increment cores were taken in six hemlock-dominated plots and two hardwood plots in 2003, totaling 217 trees sampled across 12 species. Hemlock and hardwood plots were included as separate communities. Raw data were processed as described above for CVO.

Richardson, A. D. et al. 2006. Phenology of a northern hardwood forest canopy. – Global Change Biol. 12: 1174–1188.

Precipitation and ANPP data were from the following data sets:

Boose, E., Gould, E. and Hall, B. 2002. Shaler Meteorological Station (1964–2002). Petersham, MA: Harvard Forest Data Archive: HF000. [Database]. < http://harvardforest.fas.harvard.edu:8080/exist/xquery/data.xq?id=hf000>

Boose, E. and VanScoy, M. 2010. Fisher Meteorological Station (since 2001). Petersham, MA:

Harvard Forest Data Archive: HF001. [Database].
<http://harvardforest.fas.harvard.edu:8080/exist/xquery/data.xq?id=hf001>

Bettmann-Kerson, P. and Ellison, A. 2006. Hemlock Removal Experiment - Dendrochronological Record. Petersham, MA: Harvard Forest Data Archive: HF086. [Database].
<http://harvardforest.fas.harvard.edu:8080/exist/xquery/data.xq?id=hf086>

Munger, W. and Wofsy, S. 2010. EMS Biomass Inventories - Litterfall. Petersham, MA: Harvard Forest Data Archive: HF069-07. [Database].
<http://harvardforest.fas.harvard.edu:8080/exist/xquery/data.xq?id=hf069>

Hopland Field Station (HOP)

Hopland Field Station is a 1902 ha area located in Northern California foothill rangeland. The site is dominated by annual grasses, including *Bromus*, *Festuca*, *Avena*, and *Hordeum* species. Daily precipitation data were collected from a NOAA weather station in Hopland, CA (10 km from study site). We defined the growing season as 15 October – 5 June (Murphy 1970).

ANPP was collected each year from six 4.05 m^2 (0.001 acre) grazing exclosures from 1952–1966. Collected biomass was dried at 60ºC for 48 h and weighed. Data from 1958 and 1967 were not included in the analysis due to missing precipitation data.

Murphy, A. H. 1970. Predicted forage yield based on fall precipitation in California annual grasslands. – J. Range Manage. 23: 363–365.

Hubbard Brook Experimental Forest (HBR)

Hubbard Brook Experimental Forest is a 3160 ha area in the White Mountain National Forest in New Hampshire. At the elevations sampled, the forest is dominated by deciduous species, including *Fagus grandifolia, Acer saccharum*, *Betula alleghaniensis* and *Fraxinus americana*. Daily precipitation records for three collectors in watershed 6 (litterfall) or watershed 1

(increment cores) were used. We defined the growing season as 25 April – 24 September (Richardson et al. 2006).

Litter fall was collected each November from 1993–2005 on two 100-m long transects at 525 and 585 m elevation west of the reference watershed. Higher-elevation transects were excluded from analysis because they were affected by an ice storm in 1998. Each transect had 12 baskets 0.097 m^2 in area. Additionally, 145 increment cores taken from four species in a different location in 1985 (Kim 1988) were processed using the same approach as for CVO (above) and treated as a separate 'community'.

Kim, E. S. 1988. Radial growth patterns of tree species in relation to environmental factors. – PhD thesis, Yale Univ. New Haven, CT.

Precipitation and ANPP data were from the following data sets:

Campbell, J. 2008. Daily precipitation by watershed data. Woodstock, NH: Hubbard Brook Ecosystem Study Database: 14 [Database]. <www.hubbardbrook.org/data/dataset.php?id=14>

Kim, E. S. and Bormann, F. H. 1988. Tree core increment data. Woodstock, NH: Hubbard Brook Ecosystem Study Database: 55 [Database]. <www.hubbardbrook.org/data/dataset.php?id=55>

Fahey, T. J., Hughes, J. W., Wood, C. and Wapner, S. 2006. Fine litterfall data. Woodstock, NH: Hubbard Brook Ecosystem Study Database: 49 [Database]. <www.hubbardbrook.org/data/dataset.php?id=49>

Jornada Experimental Range (JRN)

The Jornada Experimental Range is a 100 000 ha area located in southern New Mexico. Four community types within JRN were used in our analysis: black grama grassland, mesquite shrubland, creosotebush shrubland and tarbush shrubland. The black grama grassland is

dominated by *B. eriopoda*. Mesquite shrubland is the most widespread community type at JRN and is dominated by *Prosopis glandulosa*. The creosotebush shrubland and tarbush shrubland are dominated by *L. tridentata* and *Flourensia cernua*, respectively. Daily precipitation data were collected from a meteorological station at the Jornada headquarters. We defined the growing season as 25 April – 5 October (Canfield 1934).

At each site, permanent 1-m^2 quadrats are arranged in a square 7 × 7 pattern, with 10 m between each quadrat. All quadrats are measured at each site for standing biomass three times per year. Sampling occurs in February–March, May and late summer – October. At each sampling of standing biomass, all quadrats within each site are measured. Measurements include species present, and cover, height, count and phenological state of each species. Volume is then calculated for all species in all quadrats. Specified volumes of plants are harvested from nearby, and are sorted, dried, and weighed. For some species, plant material is separated into leaves, stems, and flowers, and each part is weighed separately. Regression of biomass by volume can then be constructed, and combined with volume data to calculate biomass in each quadrat.

Canfield, R. G. 1934. Stem structure of grasses on the Jornada Experimental Range. – Bot. Gaz. 95: 636–648.

Precipitation data were from the following data set:

Anderson, J. P. 2010. Climatalogical data (Jornada LTER Weather Station): Daily summary weather data. Las Cruces, NM: Jornada Data Catalog [Database]. <http://jornada-www.nmsu.edu/datacat.php#DsdClimate>

Kellogg Biological Station (KBS)

Kellogg Biological Station is an agricultural research station located in central Michigan. We used the annually burned successional field data for this analysis. The annually burned successional field is dominated by herbaceous annuals, including *Solidago canadensis*, *Poa pratensis* and *Rhus typhore*. Daily precipitation data for KBS was collected from a

meteorological station at the site headquarters. We defined the growing season as 25 – 5 September (Robinson unpubl.).

ANPP was collected from five 1-m^2 quadrats located within each community from 1990–2008. ANPP was harvested by clipping all biomass at ground level within each 1-m^2 quadrat. Collected biomass was sorted by species, dried at 60ºC for 48 h, and weighed. Data from 2007 were not included in the analysis, due to missing values. Precipitation and ANPP data were from the following data sets:

Bergsma, T. 2010. LTER daily weather (1988 to present). Hickory Corners, MI: Kellogg Biological Station Long Term Ecological Research Data Base: KBS002. [Database]. <http://lter.msu.edu/datatables/12>

Gross, K, Baker, C. and Robertson, P. 2009. Non-crop biomass (1990 to present). Hickory Corners, MI: Kellogg Biological Station Long Term Ecological Research Data Base: KBS019. [Database]. <http://lter.msu.edu/datatables/40>

Konza Prairie Biological Station (KNZ)

Konza Prairie Biological Station is a 3487 ha area of native tallgrass prairie in the Flint Hills region of northeastern Kansas. The area is dominated by warm-season C_4 grasses, particularly *Andropogon gerardii*, *Sorghastrum nutans* and *Schizachyrium scoparium*. We used data from three watersheds (ca 60 ha each) burned in the spring at either one-, four-, or twenty-year intervals (since 1973 for the four- and twenty-year burns and 1978 for the annual burn). Within each watershed, we focused on two topographic positions: 1) upland, characterized by shallow Florence soils and 2) lowland, characterized by deep Tully soils, for a total of six community types. Daily precipitation data were collected at the KNZ headquarters. The growing season was determined to span, on average, from 15 March – 1 October each year (Weaver 1954; La Pierre unpubl.).

ANPP was collected from twenty 0.1-m^2 quadrats located within each community from 1984–2008. Quadrats were placed every 10 m in a different location each year (to avoid reharvesting the same quadrat) along four permanent transects (50 m in length), with five quadrats per transect. ANPP was harvested by clipping all biomass at ground level within each 0.1-m^2 quadrat. Collected biomass was dried at 60ºC for 48 h, sorted by growth form (grass, forb, woody), and weighed. Plots with woody biomass greater than the 95th percentile were dropped from the analysis (1 quadrat). ANPP was calculated as the sum of current year's grass, forb, and woody biomass per quadrat.

Weaver, J. E. 1954. North American prairie. – Johnsen Publ. Co.

Precipitation and ANPP data were from the following data sets:

Knapp, A. K. 2008. Aboveground primary production on fire frequency treatments. Manhattan, KS: Konza Prairie Data Base: PAB01. [Database]. <www.konza.ksu.edu/datasets/knzdsdetail.aspx?currMenu=0&datasetcode=PAB01>

Briggs, J. M. 2008. Meteorological data. Manhattan, KS: Konza Prairie Data Base: AWE01. [Database]. <www.konza.ksu.edu/datasets/knzdsdetail.aspx?currMenu=0&datasetcode=AWE01>

Sevilleta National Wildlife Refuge (SEV)

The Sevilleta National Wildlife Refuge is a 100 000 ha site located in central New Mexico. Two community types within the SEV were used in our analysis: Chihuahuan Desert scrub dominated by *Larrea tridentata* and Chihuahuan Desert grassland, dominated by *Bouteloua eriopoda*. Daily precipitation data were collected from meteorological station no. 40 located within 8 km of the creosote shrubland and black grama grassland core communities. We defined the growing season as 25 March – 5 October (Doug Moore, pers. comm.).

For each community, ANPP data were collected from 80 1-m^2 permanent quadrats from

1999–2003 and 40 starting in 2004. ANPP measurements were recorded in the spring and fall of each year 1999–2009 when plant species had reached peak biomass. Regressions of weight-to-volume were developed by harvesting various sized individuals of each species from adjacent areas. A positive change in green biomass (current seasons growth) from spring to fall in each subplot was used as a measure of mean ANPP for all species (detailed methods in Huenneke et al. 2001, Muldavin et al. 2008).

Huenneke, L. F. et al. 2001. Spatial heterogeneity in Chihuahuan Desert vegetation: implications for sampling methods in semi-arid ecosystems. – J. Arid Environ. 47: 257–270.

Muldavin, E. H. et al. 2008. Aboveground net primary production dynamics in a northern Chihuahuan Desert ecosystem. – Oecologia 155: 123–132.

Precipitation and ANPP data were from the following data sets:

Moore, D. I. 1987-ongoing. Meteorology: Long-Term Ecological Research. Albuquerque, NM: Meteorological Data: SEV 001 [Database]. <http://sev.lternet.edu>

Muldavin, E. H. 1991-ongoing. Primary production: long-term ecological research. Albuquerque, NM: Seasonal and Annual Biomass and ANPP for Sevilleta LTER Core Research Sites: SEV 182 [Database]. <http://sev.lternet.edu>

Shortgrass Steppe Long-Term Ecological Research Site (SGS)

The Shortgrass Steppe Long-Term Ecological Research site is a 6280 ha area located in northern Colorado in the rain shadow of the Rocky Mountains. The area is dominated by warm-season C_4 grasses, particularly *Bouteloua gracilis* and *Buchloe dactyloides*. We used data collected from three community types separated by elevation: ridgeland, midland and swale. Daily precipitation data for SGS was collected from a meteorological station located at the station headquarters. If precipitation data were missing (1983–1996), values were filled in from a nearby NOAA weather station in Nunn, CO (24 km south of the study site). We defined the growing season as 5 April –

5 August each year, as plots were generally clipped the first week in August. The true growing season ends in September (Lauenroth and Burke 2008).

ANPP was collected from fifteen 0.25-m^2 quadrats located within each community from 1983–2006. Quadrats were placed along three permanent transects, with five quadrats per transect in a different location each year (to avoid reharvesting the same quadrat). ANPP was harvested by clipping all biomass at ground level within each quadrat. For shrub species, only current year's growth was collected. Collected biomass was dried at 60ºC for 48 h, sorted by species and weighed.

Lauenroth, W. and Burke, I. C. (eds) 2008. Ecology of the shortgrass steppe. – Oxford Univ. Press.

Precipitation and ANPP data were from the following data sets:

Parton, B. 2010. Standard Met Data: 1969–2010 Manually Collected Standard Meteorological Data. Fort Collins, CO: Shortgrass Steppe Long Term Ecological Research Site Database: man11_climdb. <http://sgs.cnr.colostate.edu/dataset_view.aspx?id=man11_climdb> (17 April 2010).

Lauenroth, W. K. 2007. Standard production data: 1983–2007 annual aboveground net primary production. Fort Collins, CO: Shortgrass Steppe Long Term Ecological Research Site Database: anpp. <http://sgs.cnr.colostate.edu/dataset_view.aspx?id=anpp> (17 April 2010).

Teakettle Experimental Forest (TEA)

The Teakettle Experimental Forest is a 1300 ha site on the western slope of the Sierra Nevada in central California. The site is dominated by *Abies concolor, Calocedrus decurrens, Pinus jeffreyi* and *Pinus lambertiana*. Daily precipitation data were collected at the Wishon Dam meteorological station (10 km from study site). Precipitation data from November 1999 were

incomplete and therefore dropped from the analysis. We defined the growing season as 15 April – 15 October (Baker 1944, Concilio et al. 2009). Dendrometer band data from an unburned, unthinned area was collected for 26 trees in four conifer species from 1997–2008. As with increment core data, dimensionless detrended mean proportional residuals (see CVO, above) were used as a production index.

Baker, F. S. 1944. Mountain climates of the western United States. – Ecol. Monogr. 14: 223–254.

Concilio, A., Chen, J. Q., Ma, S. and North, M. 2009. Precipitation drives interannual variation in summer soil respiration in a Mediterranean-climate mixed-conifer forest. – Climate Change 92: 109–122.

ANPP data previously reported by:

Hurteau, M. and North, M. 2010. Carbon recovery rates following different wildfire risk mitigation treatments. – For. Ecol. Manage. 260: 930–937.

US Sheep Experiment Station (USE)

The US Sheep Experiment Station is an 11 303 ha area spanning the border between Montana and Idaho. The area is characterized by sagebrush shrubland and is dominated by *Artemisia tripartita*, *Pseudoroegneria spicata* and *Balsamorhiza sagittata*. Daily precipitation data for USE was collected from a meteorological station at the station headquarters. We defined the growing season as 25 March – 5 August (Blaisdell 1958).

Aboveground biomass was visually estimated by growth form (woody, graminoids, forbs, and succulents) and lifespan (annual, perennial) from 1936–1954 in 125 4.65-m^2 (50 ft^2) permanent quadrats in three grazing exclosures.

Blaisdell, J. P. 1958. Seasonal development and yield of native plants on the upper Snake River plains and their relation to certain climatic factors. – In: Technical Bulletin No. 1190. USDA, Washington, D.C., pp. 1–63.

Figure A1. Location of sites that provided data for the study and mean annual precipitation.

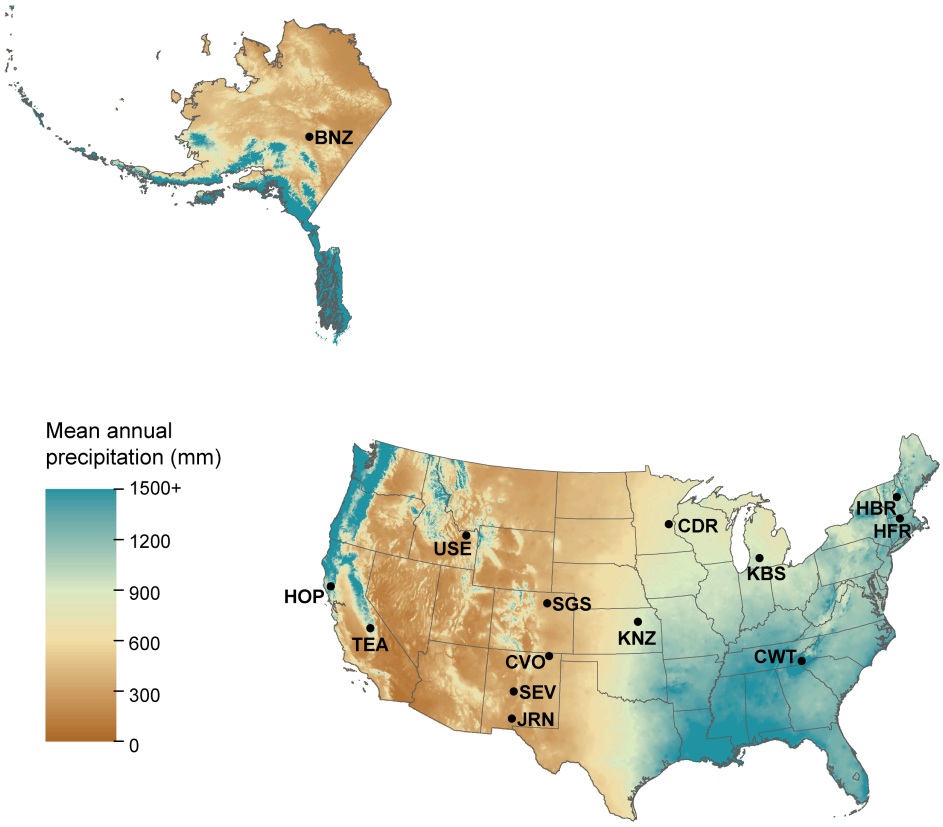

Table A1. Best statistically supported models for all communities (Com) studied where precipitation had a strong (adjusted $R^2 \geq 0.3$) and significant (overall model $p < 0.05$) effect on production. Communities that did not meet these criteria are not included in this table. Coefficient parameters and their significance are shown for each model, and sites where the total precipitation model had the most support have the most supported seasonal model included for comparison.

							Parameter coefficients (g m^{-2} mm^{-1})										
Site	Com	Model	Model rank	adj R^2	p	DF	Intercept	p0	p1	p2	p3	p4	p1*p2	p2*p3	p3*p4	pt	pg
SEV	CRE	11	best	0.33	0.036	9	10.5									0.21 *	
JRN	C	9	best (tied)	0.73	5E-04	11	22.9			0.23	0.11	0.55 ***					
		6	best (tied)	0.68	4E-04	12	22.2				0.12	0.61 ***					
	G	11	best	0.51	0.002	13	3.4									0.39 **	
	T	4	best (tied)	0.35	0.011	13	29.0					0.57 *					
BNZ	FP3	5a	best	0.43	0.027	11	181.2			5.82 **	1.94			-0.08 ***			
	FP4	9a	best	0.77	0.002	9	-168.8			6.03 ***	5.30 ***	4.63 ***		-0.07 ***	-0.05 ***		
	UP2	3	best	0.54	0.003	11	896.6				-3.31 **						
	UP3	7	best (tied)	0.49	0.014	10	244.1				-1.22 *	1.77 *					
		9	best (tied)	0.57	0.014	9	236.1			1.15	-1.48 *	1.71 *					
USE	Non	11	best	0.45	0.007	11	22.1									0.25 **	
SGS	MID	11	best	0.76	8E-09	23	-40.6									0.30 ***	
		12	best seasonal	0.70	1E-07	23	4.8										0.30 ***
	RID	11	best	0.60	3E-06	23	-24.4									0.22 ***	
		10	best seasonal	0.65	8E-05	19	-16.8	0.09	0.40 **	0.24 ***	0.18 **	0.30 ***					
	SWA	9	best (tied)	0.57	1E-04	21	-13.2			0.46 **	0.35 *	0.91 ***					
		11	best (tied)	0.53	2E-05	23	-71.2									0.49 ***	
CVO †	--	10	best	0.55	3E-06	35	-203.9	0.37	0.77 *	1.00 ***	0.49 **	-0.24					
KNZ	1f	5	best (tied)	0.58	3E-05	22	193.2			0.45 ***	0.39 ***						
		11	best (tied)	0.54	2E-05	23	133.0									0.30 ***	
	1t	5	best (tied)	0.38	0.002	22	345.8			0.49 *	0.51 **						
		5a	best (tied)	0.45	0.001	21	189.1			1.24 **	1.12 **			-0.003			
		11	best (tied)	0.31	0.002	23	291.1									0.34 **	
	20f	9	best	0.45	0.002	20	269.8			0.28 *	0.33 **	-0.35 *					
	4f	5	best (tied)	0.39	0.002	21	197.6			0.32 *	0.30 **						
		11	best (tied)	0.34	0.002	22	152.9									0.23 **	
KBS	T7	1	best	0.32	0.009	16	284.1		4.26 **								
TEA †	--	8	best	0.41	0.021	9	-710.5	1.00 *									
HFR	EMS	3	best	0.33	0.049	8	186.8				0.47 *						
CWT	118	3	best	0.40	0.029	8	45.7				0.10 *						

* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$

† ANPP data for CVO and TEA are not in units of g m^{-2} y^{-1}(Supplementary material Appendix A1); intercept and coefficients for these sites are expressed relative to the largest effect size in each model.