Spatiotemporal origin of soil water taken up by vegetation

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Vegetation modulates Earth's water, energy and carbon cycles. How its functions might change in the future largely depends on how it copes with droughts[1–4]. There is evidence that, in places and times of drought, vegetation shifts water uptake to deeper soil[5–7] and rock[8,9] moisture as well as groundwater[10–12]. Here we differentiate and assess plant use of four types of water sources: precipitation in the current month (source 1), past precipitation stored in deeper unsaturated soils and/or rocks (source 2), past precipitation stored in groundwater (source 3, locally recharged) and groundwater from precipitation fallen on uplands via river–groundwater convergence toward lowlands (source 4, remotely recharged). We examine global and seasonal patterns and drivers in plant uptake of the four sources using inverse modelling and isotope-based estimates. We find that (1), globally and annually, 70% of plant transpiration relies on source 1, 18% relies on source 2, only 1% relies on source 3 and 10% relies on source 4; (2) regionally and seasonally, source 1 is only 19% in semi-arid, 32% in Mediterranean and 17% in winter-dry tropics in the driest months; and (3) at landscape scales, source 2, taken up by deep roots in the deep vadose zone, is critical in uplands in dry months, but source 4 is up to 47% in valleys where riparian forests and desert oases are found. Because the four sources originate from different places and times, move at different spatiotemporal scales and respond with different sensitivity to climate and anthropogenic forces, understanding the space and time origins of plant water sources can inform ecosystem management and Earth system models on the critical hydrological pathways linking precipitation to vegetation.

For land plants to thrive, their root system must take up soil water. Precipitation is the ultimate source, but its intermittent nature, with dry intervals of varying durations, renders past precipitation stored in the substrates essential to plants. Deep-soil water recharged by deep infiltration in past wetter periods, and valley groundwater fed by convergence from uplands, can provide vital supplies when rain fails. In this study, we asked how much the vegetation on Earth at present relies on deep stores of past precipitation. We also asked what drives the spatiotemporal patterns of this reliance.

We distinguish four plant water sources (Fig. 1). The immediate source is soil water filled by recent rain (for example, within 1 month), called source 1 (recent precipitation). Generally, and particularly in dry regions and seasons, infiltration reaches only shallow depths, limiting the depth and amount of plant water uptake[13]. In wetter climates and times, recent precipitation meets current plant needs, with surplus percolating into deeper soils and rock fractures. As the dry season extends and shallow soil dries, roots can tap into this deep store[9,14–17], termed here as source 2 (past precipitation stored in the deep vadose zone). The wet season infiltration might also reach the water table, locally recharging the groundwater. As soils above dry out, capillary rise can supply root uptake[9–11,18–20], termed as source 3 (past precipitation stored in locally sourced groundwater). The phreatic groundwater also flows downgradient, moving precipitation surplus across space; in lowland settings (Fig. 1, left column), the groundwater might originate in adjacent uplands[12,21], termed here as source 4 (past precipitation from uplands). Plant use of sources 2 and 3 implies a temporal carryover of past hydrologic surplus to meet present deficit. Plant use of source 4 implies a spatial carryover of a neighbour's surplus but also a temporal carryover because of the travel time involved. We call sources 2, 3 and 4 'total past-precipitation use'. It is such spatiotemporal carryovers of past precipitation that free land plants from complete reliance on recent precipitation, ensuring plant survival and continued growth through droughts.

We test four hypotheses: globally, vegetation reliance on past precipitation is widespread, even in humid climates punctuated by droughts (H1). Regionally, the degree of this reliance depends on climatic water stress, which is highest in seasonally wet–dry climates where wet season surplus fills the deep store, and dry season deficit demands it; in true aridity, precipitation is insufficient to fill the deep store (H2). At the landscape scale, reliance on past precipitation varies with drainage position, with upland plants using deep vadose zone store (source 2) and lowland plants using shallow groundwater (sources 3 and 4) (H3). At the individual plant level, reliance on past precipitation depends on growth form, with larger trees more demanding and capable of tapping

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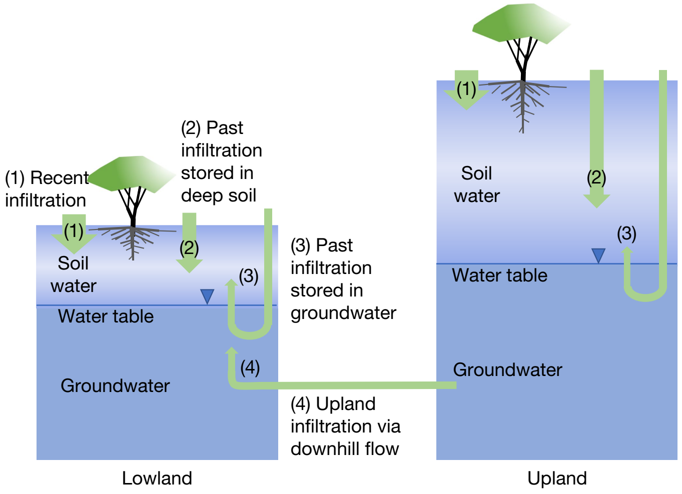

Fig. 1 | Schematic of four plant water sources. Lowlands (left) and uplands (right) are connected by down-valley flow. Arrow width indicates event frequency. Source 1: soil water from recent infiltration. Source 2: deep vadose zone water recharged by past rain. Source 3: groundwater locally recharged by past rain. Source 4: groundwater remotely recharged by upland rain. Note the shallow water table in lowlands and the thick vadose zone in uplands.

into deeper stores; it is species specific, with those adapted to season-dry climates making the most use of past precipitation (H4).

To test H1 and H2 on global to regional patterns, we simplify the Köppen–Geiger climate classification[22] (Supplementary Information 1) into 13 water stress types in four groups (Supplementary Fig. 1): low water stress in moist tropical, temperate and cool climates; high seasonal stress in Mediterranean, monsoon and subtropical climates; high perennial stress in arid steppes; and minimum vegetation in deserts. For testing H1–H3 (climate and drainage), we use global inverse modelling (Supplementary Information 2) corroborated by isotope-based estimates (Supplementary Information 3). For testing H4 on growth form and species, we use isotope-based estimates (Supplementary Information 3).

The natural abundance of stable isotopes of oxygen and hydrogen in plant xylem and source waters offers a useful tracer of plant water source[23–25]. We compiled such studies from the literature (Supplementary Information 3). However, these studies do not report plant water use as the four sources defined here but, rather, contributions from different soil depths regardless of the time of recharge. Some studies include isotopically distinct seasonal precipitation as endmembers, which are used to differentiate recent versus past precipitation. Some studies differentiate deep soil from groundwater, but the groundwater origin (past versus recent and local versus remote recharge) is unclear. In our compilation, we recast the uptake depths into the four sources aided by information on seasonal isotopic signatures of precipitation and soil–water response to precipitation events at different depth (inferring infiltration depths). The uncertainties in this recasting (Supplementary Information 3), the scarcity of studies (Extended Data Fig. 1), the known discrepancy among different laboratories using cryogenic vacuum distillation for water extraction[26,27] and sampling bias toward dry places and times and better-funded nations demand a global modelling approach that is corroborated by isotope estimates where and when available.

The time scale that we define as recent precipitation in the model is 1 month—an arbitrary but useful interval to quantify seasonal dynamics. The sampling frequency in isotope studies varies widely, and we follow the authors' broad description of wet versus dry periods.

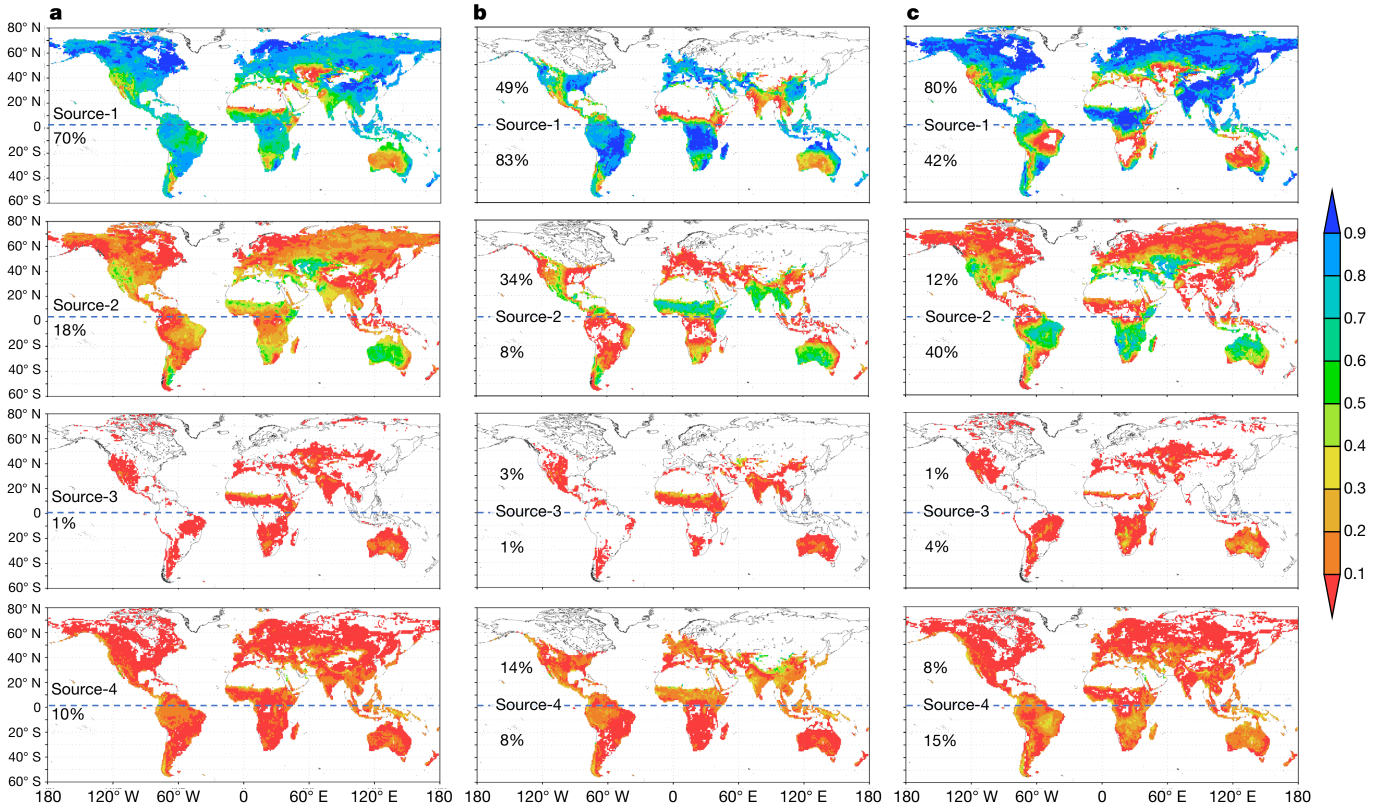

Fig. 2 | Modelled fractional source contributions to transpiration. **a**–**c**, Annual, global data (**a**), hemispheric data for February (**b**) and hemispheric data for August (**c**). Colour scales indicate fraction of annual transpiration (dimensionless). Maps are aggregated from a 30′ model grid to 1° × 1° for display. Higher-resolution maps are in Supplementary Fig. 8.

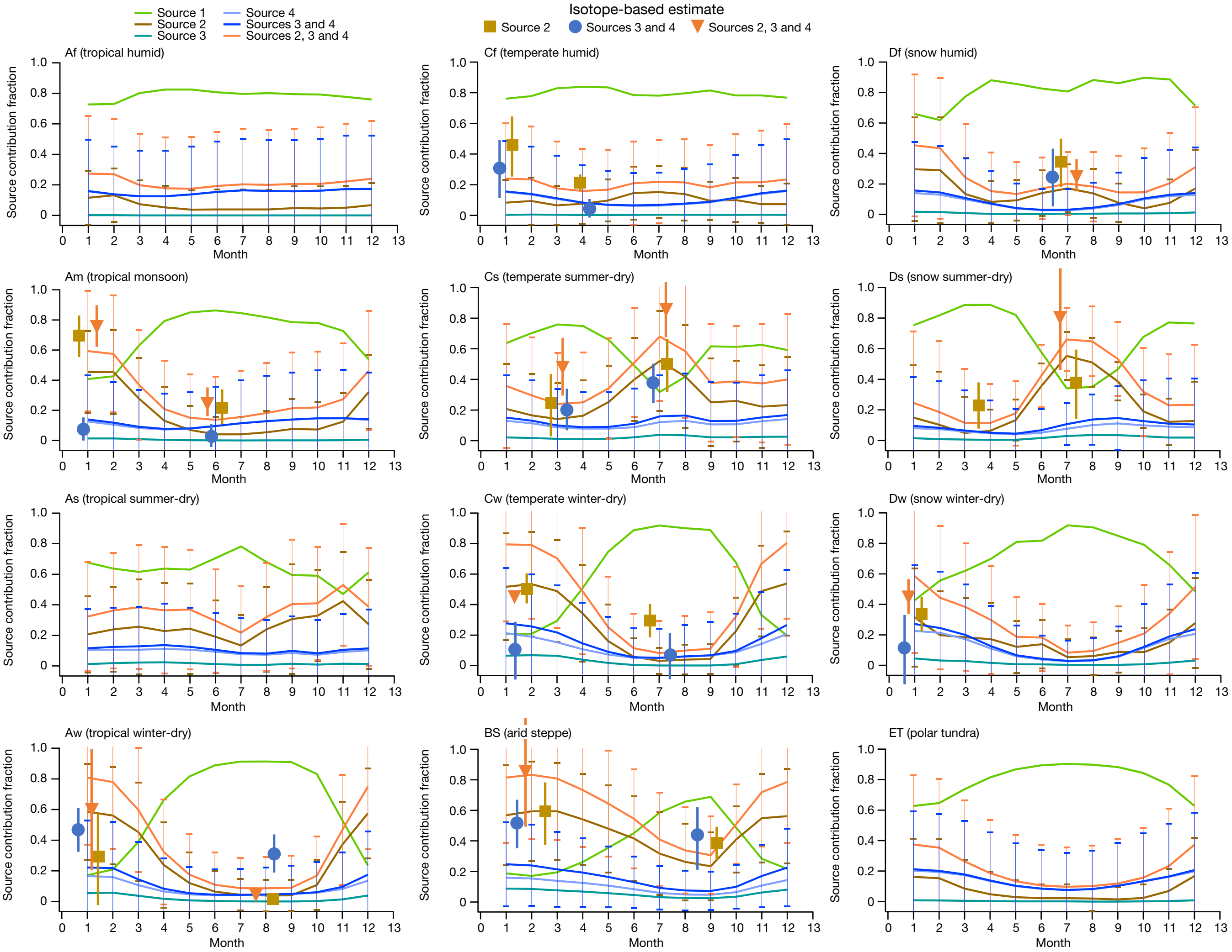

Fig. 3 | Monthly source contribution to transpiration for the 12 climate types in the model. Lines are the monthly mean of model results with 1 s.d. among model grid cells under each climate (sample sizes in Table S5). Symbols are isotope-based estimates for wet and dry periods, showing mean and 1 s.d. among individual plants (sample sizes in Table S8). Southern Hemisphere results are shifted by 6 months.

Uptake source from inverse modelling

A full model description is provided in Supplementary Information 2. In brief, the model adopts a global grid of 30 arcseconds (about 1 km) to delineate upland versus lowland within computation limits, at hourly steps over a 10-year span (2003–2013) resolving event-to-seasonal dynamics. Our model has four parts: (1) soil groundwater hydrology forced by atmosphere-reanalysis and soil properties and land topography, giving infiltration, soil water profile and water table depth at each hour and grid; (2) ecosystem transpiration from satellite leaf area index and atmosphere-reanalysis, giving plant water demand to be met by root uptake; (3) inversion of root uptake profile using Ohm's law, leading to higher uptake from wetter/shallower soil layers; and (4) computation of the four source contributions to monthly transpiration from the soil water mass balance. Tracking lateral flow among grid cells, we separate local (source 3) and upland (source 4) groundwater origins. Several previous inverse model studies quantified the necessary rooting depth to meet transpiration demands, but they neglected groundwater and did not differentiate among sources 2, 3 and 4 (detailed intercomparisons in Supplementary Information 2.9).

Model monthly evapotranspiration is compared with observations at 103 eddy-covariance flux towers[28] (Supplementary Fig. 5) worldwide and model river discharge compared to observations at 34 river gauges (Supplementary Fig. 6). Without any calibration, the model reproduces well the seasonal water balance worldwide. Discrepancies are largely due to neglecting anthropogenic activities in the model (irrigation and reservoir regulation). Monthly evapotranspiration comparisons (Supplementary Table 3, Supplementary Fig. 7) suggest slight model underestimation globally or conservative estimates of plant use of past precipitation.

To test H1, that vegetation reliance on past precipitation is globally prevalent and important, Fig. 2 gives the 10-year mean source contribution to transpiration. Globally and annually (Fig. 2a), source 1 accounts for 70% (s.d. 24%) of transpiration, source 2 for 18% (s.d. 15%), source 3 for only 1% (s.d. 3%) and source 4 for 10% (s.d. 22%) (that is, groundwater use is primarily source 4 recharged in uplands). Seasonally, source 1 is only 49% in February in the Northern Hemisphere (Fig. 2b) and 42% in August in the Southern Hemisphere (Fig. 2c). In the southern hemispheric dry season, 58% of transpiration is from past precipitation (Extended Data Table 1, orange font).

To test H2, that—at regional scales—reliance on past precipitation depends on climatic water stress, which is highest in semi-arid and season-arid climates, we rank climate types by annual past-precipitation use (Extended Data Table 2). The order is arid steppe (BS 53%, bold font), summer-dry (Cs 43%, Ds 41% and As 36%), winter-dry (Cw 33%,

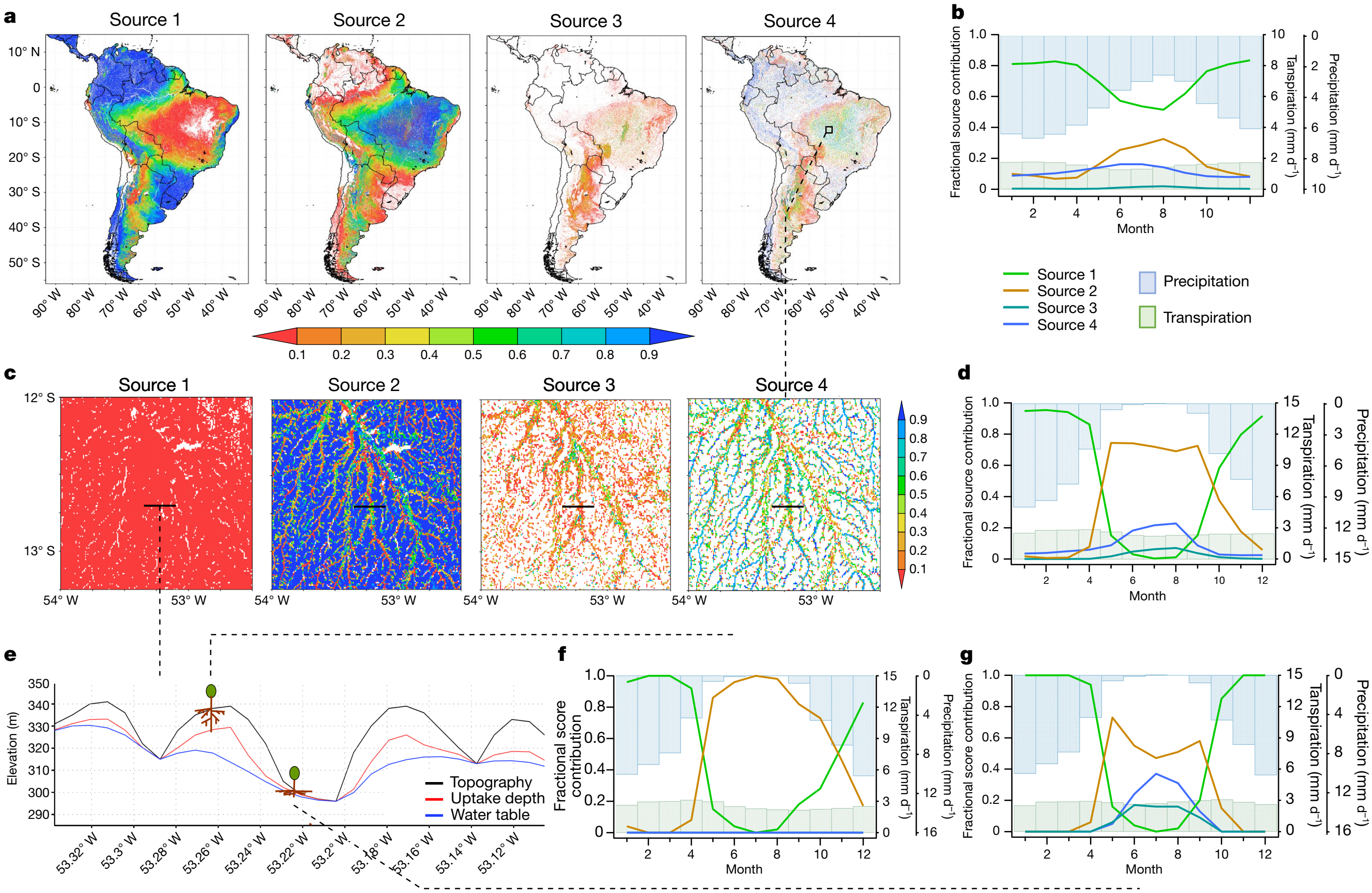

Fig. 4 | Modelled source contributions in South America at the continent-to-hillslope scale. a–g, Source contributions at continent scale (**a**) during August (dry season) and their seasonal variations (**b**), source contributions at landscape scale (**c**) over Xingu National Park (location in **a**) and seasonal variations (**d**), source contributions at hill-valley scale (**e**, location in **c**) and seasonal variation for hill (**f**) and valley (**g**) position. Colour scale indicates fraction of annual transpiration.

Aw 31% and Am 29%), humid (Af 21%, Cf 20% and Df 17%), cold winter-dry and tundra (Dw and ET, both 15%). In the driest month, past precipitation use is much higher (red font), reaching 83% in BS, 68% in Cs, 66% in Ds, 53% in As, 80% in Cw, 81% in Aw and 59% in Am. Seasonal shifts in plant water source (lines with one standard deviation) are shown in Fig. 3 for all climates. Except for the humid Af and Cf climate, a pronounced shift occurs from using recent precipitation in wet months to past precipitation in dry months. This shift is widely reported in isotope-based studies of individual plants[6,7,29], and here we show that it may be prevalent at the ecosystem level and worldwide. The large spread in model results (among 1-km grid cells) under any given climate point to the sub-climate-scale drivers of water source partitioning, among which is land drainage.

To test H3, that, at landscape scales—under the same climate—drainage position affects source partitioning, we separate model grid cells into upland (losing groundwater) versus lowland (gaining groundwater) for each month and each water stress group (low, seasonal and high; Extended Data Table 3). In all groups, upland plants used more source 1 (compare green fonts in each group), and lowland plants used more source 4 (blue fonts, groundwater sourced remotely), accounting for 18–29% of annual (blue font) and 36–47% of dry-month uptake (red font). This upland–lowland contrast is displayed in the full-resolution maps in Supplementary Fig. 8 where the strong hill and valley contrast is clearly visible. In dry climates and seasons, topography-driven lateral convergence can sustain gallery/riparian forests and desert oases that would otherwise not exist.

Uptake source from isotope-based studies

The very limited isotope-based estimates (Extended Data Fig. 1, Extended Data Table 4) support the model regarding H1 and H2 on global and regional patterns of plant water source partitioning, across wet and dry seasons. These estimates plot closely to the model mean or within one standard deviation (Fig. 3), the latter reflecting the large variation among millions of model grid cells (in drainage, soil and vegetation) within each climate. Ranked by dry-season (best sampled) values (orange font, Extended Data Table 4), avoiding small samples, the highest is Cs, reaching 89 ± 16% (versus 68% in the model in the driest month; Extended Data Table 2), BS 85 ± 35% (versus 83% in the model), BW 67 ± 23% (not included in the model due to undetectable leaf area index by satellites) and Aw 60 ± 39% (versus 81% in the model). Globally and over the growing season, the limited isotope results suggest 50 ± 21% (versus 30% in model) plant use of past precipitation. The higher isotope values are due to preferential sampling of larger plants in drier places and times, biased-low model ET (Table S3, Fig. S7) by averaging leaf area index over 1-km grid cells and using monthly results, whereas isotope samples are point snapshots. Isotope-based results also support the model on H3 (drainage position) (Extended Data Table 5); valley plants used more groundwater across all water stress groups (blue font).

To test H4 (part 1), that—at the individual plant level—larger plants use more past precipitation, we rank the dry-season plant use of past precipitation by growth form (Extended Data Table 6, orange font). Results weakly support H4; larger woody plants used more past precipitation than forbs and grasses. To test H4 (part 2), that taxa adapted to aridity use more past precipitation, dry season results are given for the ten best observed genera (Extended Data Table 7). The top ranking are arid riparian trees (*Populus* and *Tamarix*) and those characteristic of season-arid (*Quercus* and *Eucalyptus*) and arid (*Banksia*, *Artemisia* and *Caragana*) climates. The lowest ranking is *Ficus* in the humid tropics, although humid climates are severely undersampled.

Case study of South America and Amazonia

Figure 4 presents modelled spatiotemporal patterns of water source partitioning over South America at continent, landscape and hill-valley scales in August (dry season). Continental patterns (Fig. 4a, b) reflect the climate; ecosystems in the strongly seasonal southeast Amazon (5-month dry season) depend the most on source 2. Regional topography also matters; the LaPlata valley in Argentina receives river and groundwater from the Andes, so its ecosystems depend on source 4 (ref. [12]) (see Supplementary Fig. 8l for details). At the landscape (Fig. 4c, d) and hill-valley (Fig. 4e–g) scales, topography dominates the patterns in source partitioning[30]. Upland ecosystems used exclusively sources 1 and 2 (rain-fed), with source 2 reaching 90% in the late dry season (Fig. 4f), but valley ecosystems depended on groundwater (Fig. 4g), reaching more than 50% in the driest months.

Our estimate of 30% global annual ecosystem use of past precipitation is substantial, but it fails to convey its disproportionate importance: it ensures plant survival, continued growth and functioning in water-stressed places and times. Semi-arid ecosystems are recognized as key regulators of inter-annual variations in terrestrial carbon sink[31,32], and here we show that they are particularly well adapted to using past precipitation and remote precipitation to overcome seasonal and irregular droughts. Our preliminary estimates of space and time origins of plant water sources represent only a first step in quantifying the global importance of subsurface water storage and transport in sustaining land ecosystems, inviting further quantification from both coordinated field measurements of plant water sources and more realistic descriptions of hydrologic flow paths in Earth system models.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-021-03958-6.

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Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this paper.

Data availability

All model input data are generated by government and research agencies and are in the public domain. Links to download these data are provided in Supplementary Table 2. Modelled monthly transpiration and source contributions (sources 1, 2, 3 and 4) for each continent and month can be downloaded at the following public repository via ftp: http://thredds-gfnl.usc.es/thredds/catalog/DATA_TRANSPSOURCES/catalog.html. The isotope compilation can also be found in an Excel spreadsheet at the above ftp site.

Code availability

Our model code, written in Fortran, was uploaded to GitHub: https://github.com/gmiguez/MMF-HYDROMODEL.

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Author contributions G.M.-M. performed model simulations and analyses. Y.F. compiled and analysed isotope estimates. Y.F. and G.M.-M. wrote the manuscript.

Competing interests The authors declare no competing interests.

Additional information

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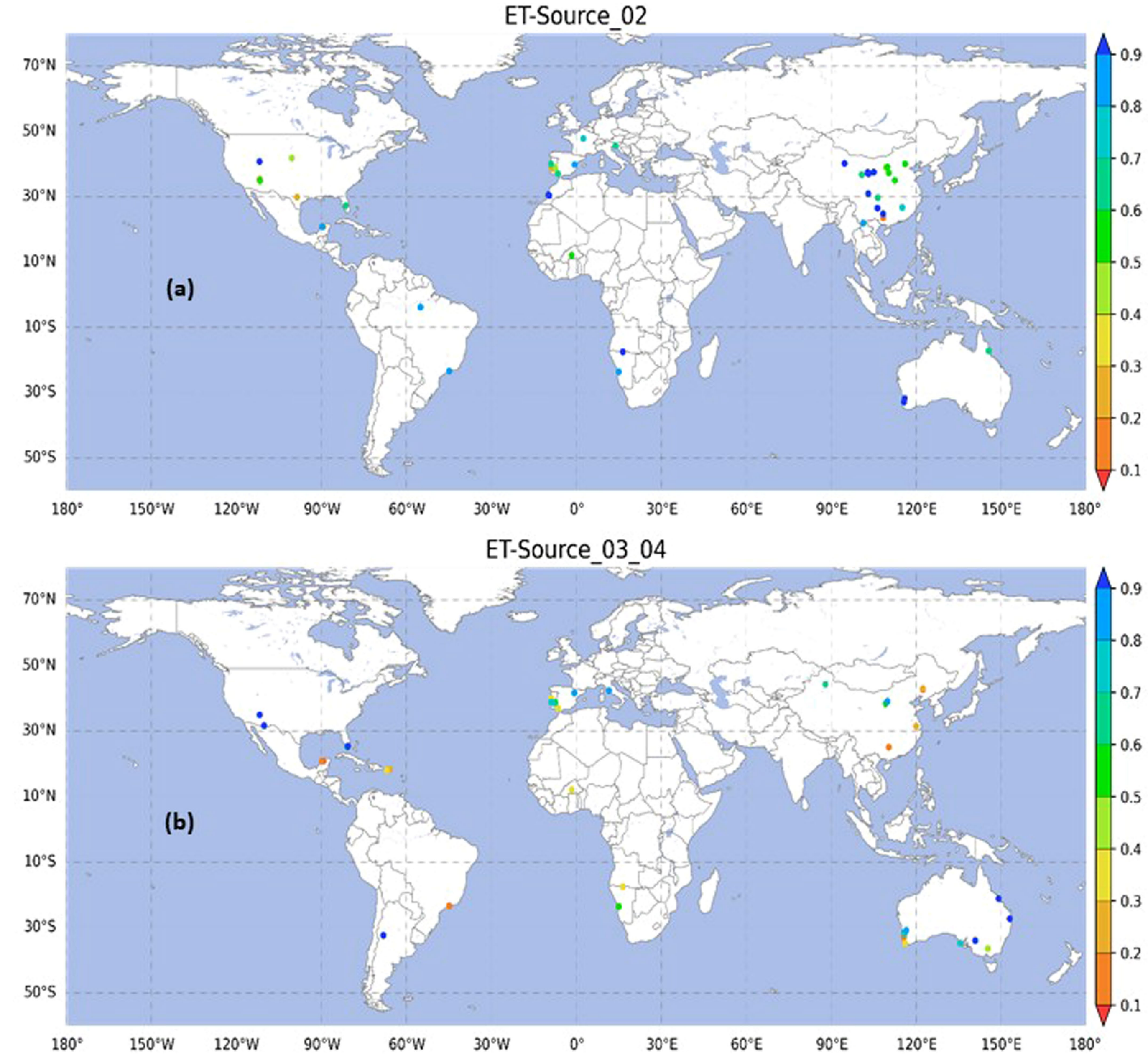


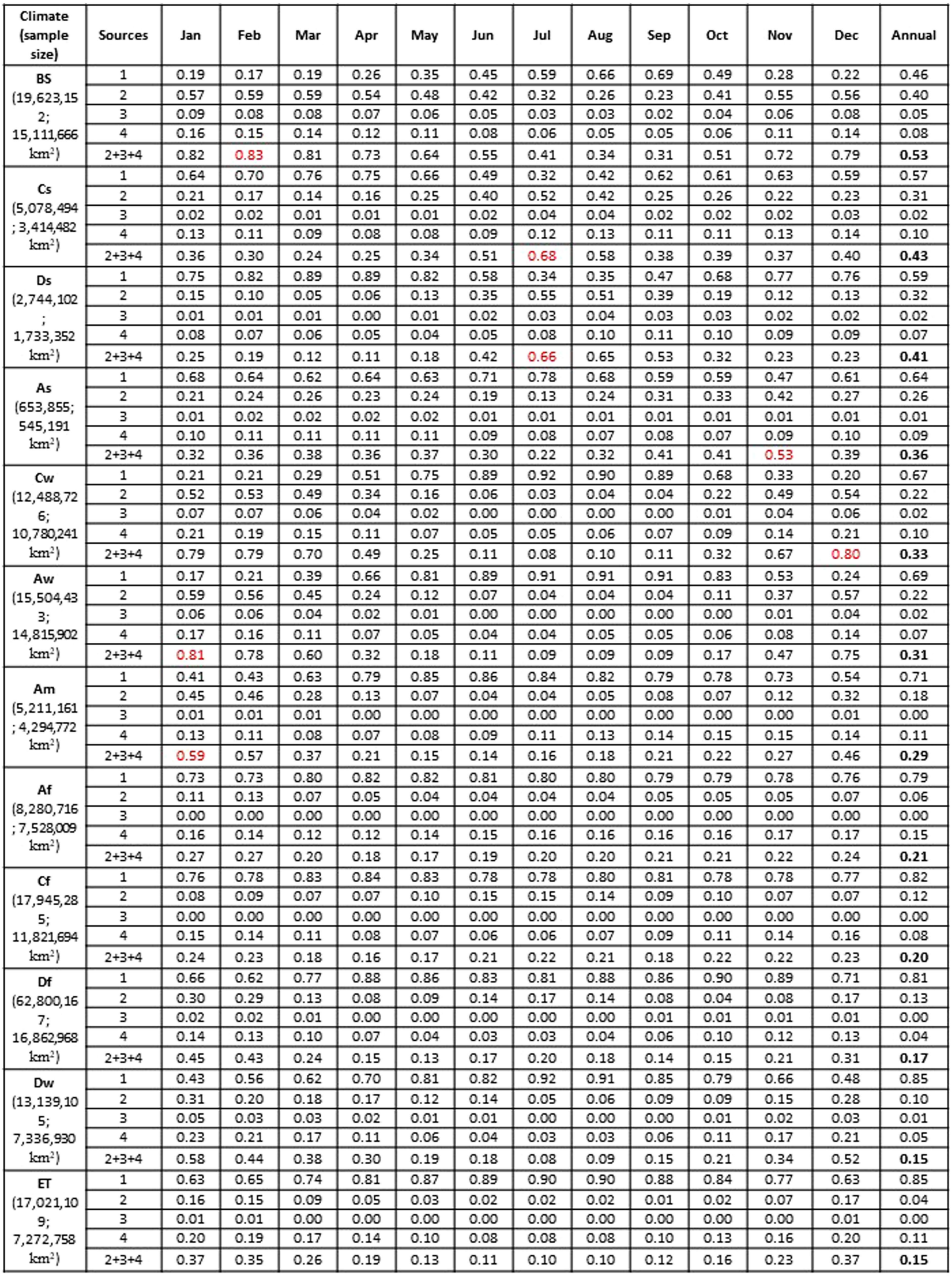
Extended Data Fig. 1 | Isotope-based estimates of fractional contribution to plant xylem water. (a) Source-2 and (b) Source-3+4 (undistinguished isotopically) during dry periods (best sampled). Where species are sampled at the same location (dots overlapping), the highest is displayed on the top.

Extended Data Table 1 | Modelled fractional contribution from the four water sources to monthly transpiration as global and hemispheric average

Sources	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
	Global												
1	0.71	0.72	0.74	0.72	0.70	0.67	0.68	0.68	0.72	0.72	0.69	0.70	**0.70**
2	0.18	0.17	0.15	0.16	0.19	0.21	0.21	0.21	0.17	0.17	0.20	0.19	**0.18**
3	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.02	**0.01**
4	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.10	0.10	**0.10**
2+3+4	0.29	0.28	0.26	0.28	0.30	0.33	0.32	0.32	0.28	0.28	0.31	0.30	**0.30**
	Northern Hemisphere												
1	0.44	**0.49**	0.59	0.70	0.77	0.77	0.78	**0.80**	0.82	0.74	0.58	0.47	**0.71**
2	0.37	**0.34**	0.26	0.18	0.14	0.15	0.15	**0.12**	0.09	0.15	0.28	0.35	**0.18**
3	0.04	**0.03**	0.03	0.02	0.01	0.01	0.01	**0.01**	0.01	0.01	0.02	0.03	**0.01**
4	0.16	**0.14**	0.12	0.10	0.08	0.07	0.07	**0.08**	0.08	0.10	0.12	0.15	**0.10**
2+3+4	0.56	0.51	0.41	0.30	0.23	0.23	0.22	0.20	0.18	0.26	0.42	0.53	**0.29**
	Southern Hemisphere												
1	0.83	**0.83**	0.83	0.75	0.59	0.46	0.42	**0.42**	0.55	0.70	0.78	0.82	**0.70**
2	0.09	**0.08**	0.08	0.14	0.26	0.36	0.38	**0.40**	0.31	0.20	0.13	0.10	**0.19**
3	0.01	**0.01**	0.01	0.01	0.02	0.03	0.03	**0.04**	0.03	0.02	0.01	0.01	**0.01**
4	0.07	**0.08**	0.09	0.10	0.13	0.16	0.16	**0.15**	0.11	0.09	0.08	0.07	**0.10**
2+3+4	0.17	0.17	0.17	0.25	0.41	0.54	**0.58**	**0.58**	0.45	0.31	0.22	0.18	**0.30**

Blue fonts indicate values shown in Fig. 2.

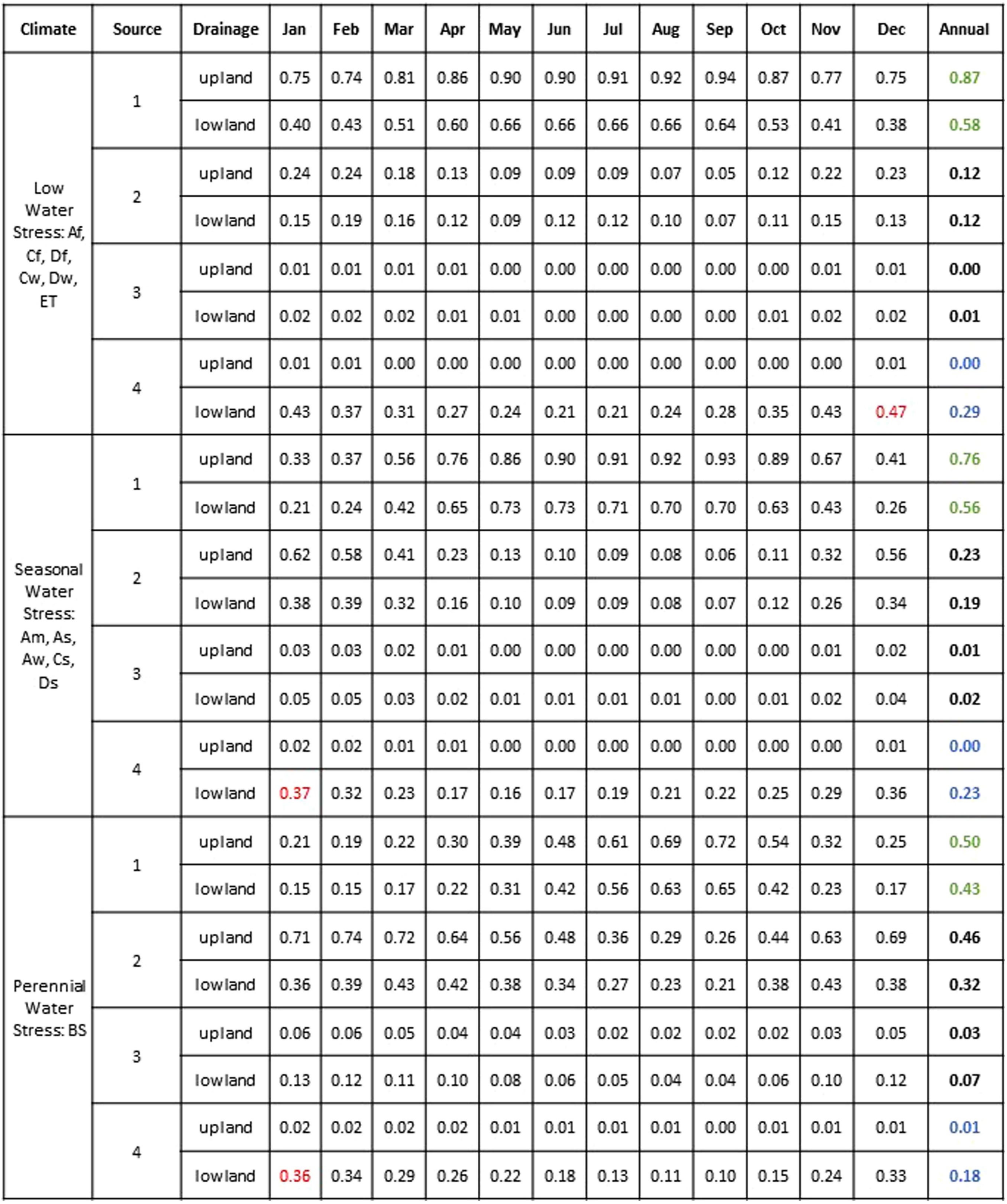
Extended Data Table 2 | Modelled fractional contribution of four water sources to monthly transpiration for the 12 climatic types represented in the model, ranked by annual plant uptake of total past precipitation (Source-2+3+4, bold font)



Climate (sample size)	Sources	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
BS (19,623,152; 15,111,666 km^2)	1	0.19	0.17	0.19	0.26	0.35	0.45	0.59	0.66	0.69	0.49	0.28	0.22	0.46
	2	0.57	0.59	0.59	0.54	0.48	0.42	0.32	0.26	0.23	0.41	0.55	0.56	0.40
	3	0.09	0.08	0.08	0.07	0.06	0.05	0.03	0.03	0.02	0.04	0.06	0.08	0.05
	4	0.16	0.15	0.14	0.12	0.11	0.08	0.06	0.05	0.05	0.06	0.11	0.14	0.08
	2+3+4	0.82	0.83	0.81	0.73	0.64	0.55	0.41	0.34	0.31	0.51	0.72	0.79	**0.53**
Cs (5,078,494; 3,414,482 km^2)	1	0.64	0.70	0.76	0.75	0.66	0.49	0.32	0.42	0.62	0.61	0.63	0.59	0.57
	2	0.21	0.17	0.14	0.16	0.25	0.40	0.52	0.42	0.25	0.26	0.22	0.23	0.31
	3	0.02	0.02	0.01	0.01	0.01	0.02	0.04	0.04	0.02	0.02	0.02	0.03	0.02
	4	0.13	0.11	0.09	0.08	0.08	0.09	0.12	0.13	0.11	0.11	0.13	0.14	0.10
	2+3+4	0.36	0.30	0.24	0.25	0.34	0.51	0.68	0.58	0.38	0.39	0.37	0.40	**0.43**
Ds (2,744,102; 1,733,352 km^2)	1	0.75	0.82	0.89	0.89	0.82	0.58	0.34	0.35	0.47	0.68	0.77	0.76	0.59
	2	0.15	0.10	0.05	0.06	0.13	0.35	0.55	0.51	0.39	0.19	0.12	0.13	0.32
	3	0.01	0.01	0.01	0.00	0.01	0.02	0.03	0.04	0.03	0.03	0.02	0.02	0.02
	4	0.08	0.07	0.06	0.05	0.04	0.05	0.08	0.10	0.11	0.10	0.09	0.09	0.07
	2+3+4	0.25	0.19	0.12	0.11	0.18	0.42	0.66	0.65	0.53	0.32	0.23	0.23	**0.41**
As (653,855; 545,191 km^2)	1	0.68	0.64	0.62	0.64	0.63	0.71	0.78	0.68	0.59	0.59	0.47	0.61	0.64
	2	0.21	0.24	0.26	0.23	0.24	0.19	0.13	0.24	0.31	0.33	0.42	0.27	0.26
	3	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	4	0.10	0.11	0.11	0.11	0.11	0.09	0.08	0.07	0.08	0.07	0.09	0.10	0.09
	2+3+4	0.32	0.36	0.38	0.36	0.37	0.30	0.22	0.32	0.41	0.41	0.53	0.39	**0.36**
Cw (12,488,726; 10,780,241 km^2)	1	0.21	0.21	0.29	0.51	0.75	0.89	0.92	0.90	0.89	0.68	0.33	0.20	0.67
	2	0.52	0.53	0.49	0.34	0.16	0.06	0.03	0.04	0.04	0.22	0.49	0.54	0.22
	3	0.07	0.07	0.06	0.04	0.02	0.00	0.00	0.00	0.00	0.01	0.04	0.06	0.02
	4	0.21	0.19	0.15	0.11	0.07	0.05	0.05	0.06	0.07	0.09	0.14	0.21	0.10
	2+3+4	0.79	0.79	0.70	0.49	0.25	0.11	0.08	0.10	0.11	0.32	0.67	0.80	**0.33**
Aw (15,504,433; 14,815,902 km^2)	1	0.17	0.21	0.39	0.66	0.81	0.89	0.91	0.91	0.91	0.83	0.53	0.24	0.69
	2	0.59	0.56	0.45	0.24	0.12	0.07	0.04	0.04	0.04	0.11	0.37	0.57	0.22
	3	0.06	0.06	0.04	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.02
	4	0.17	0.16	0.11	0.07	0.05	0.04	0.04	0.05	0.05	0.06	0.08	0.14	0.07
	2+3+4	0.81	0.78	0.60	0.32	0.18	0.11	0.09	0.09	0.09	0.17	0.47	0.75	**0.31**
Am (5,211,161; 4,294,772 km^2)	1	0.41	0.43	0.63	0.79	0.85	0.86	0.84	0.82	0.79	0.78	0.73	0.54	0.71
	2	0.45	0.46	0.28	0.13	0.07	0.04	0.04	0.05	0.08	0.07	0.12	0.32	0.18
	3	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
	4	0.13	0.11	0.08	0.07	0.08	0.09	0.11	0.13	0.14	0.15	0.15	0.14	0.11
	2+3+4	0.59	0.57	0.37	0.21	0.15	0.14	0.16	0.18	0.21	0.22	0.27	0.46	**0.29**
Af (8,280,716; 7,528,009 km^2)	1	0.73	0.73	0.80	0.82	0.82	0.81	0.80	0.80	0.79	0.79	0.78	0.76	0.79
	2	0.11	0.13	0.07	0.05	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.07	0.06
	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	4	0.16	0.14	0.12	0.12	0.14	0.15	0.16	0.16	0.16	0.16	0.17	0.17	0.15
	2+3+4	0.27	0.27	0.20	0.18	0.17	0.19	0.20	0.20	0.21	0.21	0.22	0.24	**0.21**
Cf (17,945,285; 11,821,694 km^2)	1	0.76	0.78	0.83	0.84	0.83	0.78	0.78	0.80	0.81	0.78	0.78	0.77	0.82
	2	0.08	0.09	0.07	0.07	0.10	0.15	0.15	0.14	0.09	0.10	0.07	0.07	0.12
	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	4	0.15	0.14	0.11	0.08	0.07	0.06	0.06	0.07	0.09	0.11	0.14	0.16	0.08
	2+3+4	0.24	0.23	0.18	0.16	0.17	0.21	0.22	0.21	0.18	0.22	0.22	0.23	**0.20**
Df (62,800,167; 16,862,968 km^2)	1	0.66	0.62	0.77	0.88	0.86	0.83	0.81	0.88	0.86	0.90	0.89	0.71	0.81
	2	0.30	0.29	0.13	0.08	0.09	0.14	0.17	0.14	0.08	0.04	0.08	0.17	0.13
	3	0.02	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00
	4	0.14	0.13	0.10	0.07	0.04	0.03	0.03	0.04	0.06	0.10	0.12	0.13	0.04
	2+3+4	0.45	0.43	0.24	0.15	0.13	0.17	0.20	0.18	0.14	0.15	0.21	0.31	**0.17**
Dw (13,139,105; 7,336,930 km^2)	1	0.43	0.56	0.62	0.70	0.81	0.82	0.92	0.91	0.85	0.79	0.66	0.48	0.85
	2	0.31	0.20	0.18	0.17	0.12	0.14	0.05	0.06	0.09	0.09	0.15	0.28	0.10
	3	0.05	0.03	0.03	0.02	0.01	0.01	0.00	0.00	0.00	0.01	0.02	0.03	0.01
	4	0.23	0.21	0.17	0.11	0.06	0.04	0.03	0.03	0.06	0.11	0.17	0.21	0.05
	2+3+4	0.58	0.44	0.38	0.30	0.19	0.18	0.08	0.09	0.15	0.21	0.34	0.52	**0.15**
ET (17,021,109; 7,272,758 km^2)	1	0.63	0.65	0.74	0.81	0.87	0.89	0.90	0.90	0.88	0.84	0.77	0.63	0.85
	2	0.16	0.15	0.09	0.05	0.03	0.02	0.02	0.02	0.01	0.02	0.07	0.17	0.04
	3	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
	4	0.20	0.19	0.17	0.14	0.10	0.08	0.08	0.08	0.10	0.13	0.16	0.20	0.11
	2+3+4	0.37	0.35	0.26	0.19	0.13	0.11	0.10	0.10	0.12	0.16	0.23	0.37	**0.15**

Sample size (Column-1) is the number of 30″ model grid cells and area (km^2) under each climate.

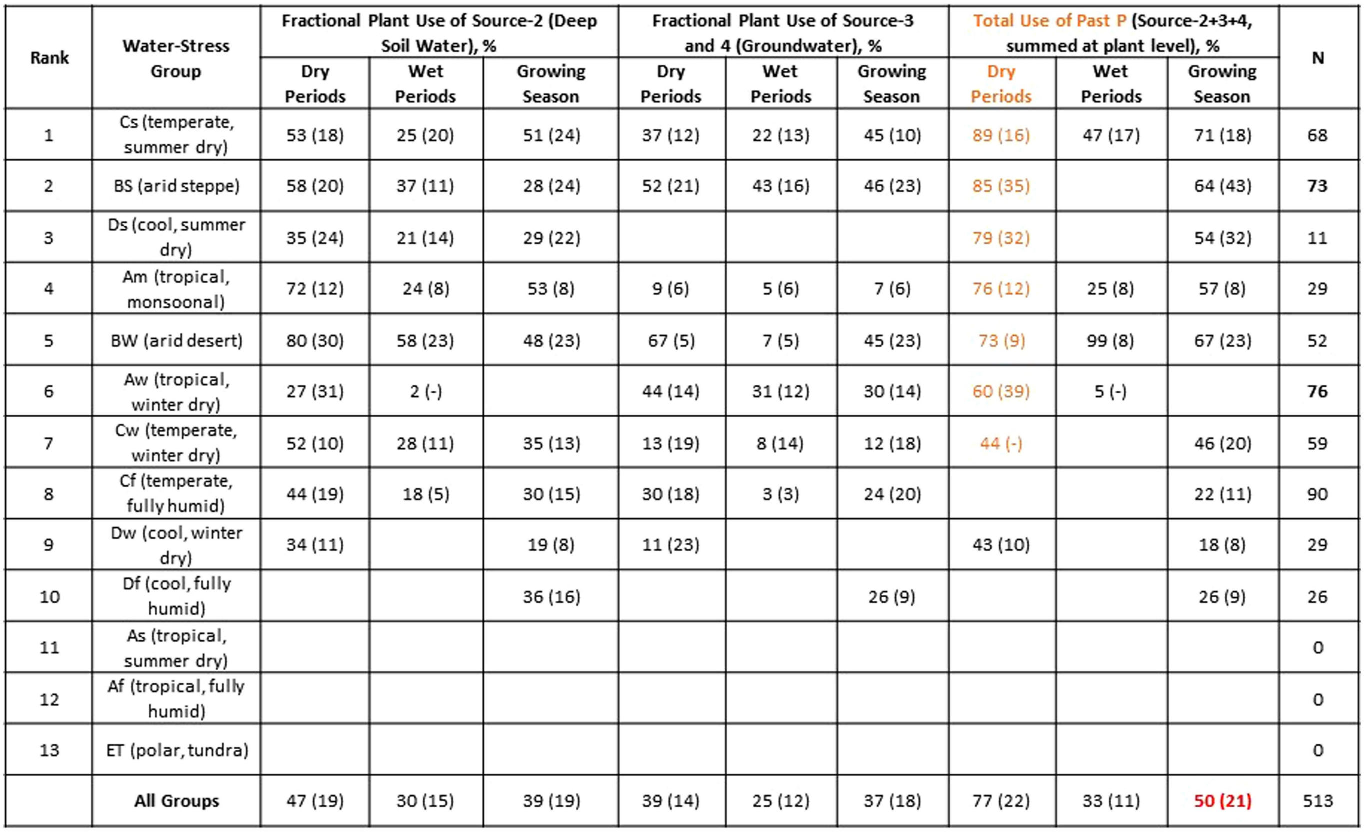
Extended Data Table 3 | Modelled plant water source by drainage positions, for low, seasonal and perennial water stress groups



Climate	Source	Drainage	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Low Water Stress: Af, Cf, Df, Cw, Dw, ET	1	upland	0.75	0.74	0.81	0.86	0.90	0.90	0.91	0.92	0.94	0.87	0.77	0.75	0.87
		lowland	0.40	0.43	0.51	0.60	0.66	0.66	0.66	0.66	0.64	0.53	0.41	0.38	0.58
	2	upland	0.24	0.24	0.18	0.13	0.09	0.09	0.09	0.07	0.05	0.12	0.22	0.23	**0.12**
		lowland	0.15	0.19	0.16	0.12	0.09	0.12	0.12	0.10	0.07	0.11	0.15	0.13	**0.12**
	3	upland	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	**0.00**
		lowland	0.02	0.02	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.02	0.02	**0.01**
	4	upland	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
		lowland	0.43	0.37	0.31	0.27	0.24	0.21	0.21	0.24	0.28	0.35	0.43	0.47	0.29
Seasonal Water Stress: Am, As, Aw, Cs, Ds	1	upland	0.33	0.37	0.56	0.76	0.86	0.90	0.91	0.92	0.93	0.89	0.67	0.41	0.76
		lowland	0.21	0.24	0.42	0.65	0.73	0.73	0.71	0.70	0.70	0.63	0.43	0.26	0.56
	2	upland	0.62	0.58	0.41	0.23	0.13	0.10	0.09	0.08	0.06	0.11	0.32	0.56	**0.23**
		lowland	0.38	0.39	0.32	0.16	0.10	0.09	0.09	0.08	0.07	0.12	0.26	0.34	**0.19**
	3	upland	0.03	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	**0.01**
		lowland	0.05	0.05	0.03	0.02	0.01	0.01	0.01	0.01	0.00	0.01	0.02	0.04	**0.02**
	4	upland	0.02	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
		lowland	0.37	0.32	0.23	0.17	0.16	0.17	0.19	0.21	0.22	0.25	0.29	0.36	0.23
Perennial Water Stress: BS	1	upland	0.21	0.19	0.22	0.30	0.39	0.48	0.61	0.69	0.72	0.54	0.32	0.25	0.50
		lowland	0.15	0.15	0.17	0.22	0.31	0.42	0.56	0.63	0.65	0.42	0.23	0.17	0.43
	2	upland	0.71	0.74	0.72	0.64	0.56	0.48	0.36	0.29	0.26	0.44	0.63	0.69	**0.46**
		lowland	0.36	0.39	0.43	0.42	0.38	0.34	0.27	0.23	0.21	0.38	0.43	0.38	**0.32**
	3	upland	0.06	0.06	0.05	0.04	0.04	0.03	0.02	0.02	0.02	0.02	0.03	0.05	**0.03**
		lowland	0.13	0.12	0.11	0.10	0.08	0.06	0.05	0.04	0.04	0.06	0.10	0.12	**0.07**
	4	upland	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01
		lowland	0.36	0.34	0.29	0.26	0.22	0.18	0.13	0.11	0.10	0.15	0.24	0.33	0.18

Coloured fonts indicate values mentioned in the main text.

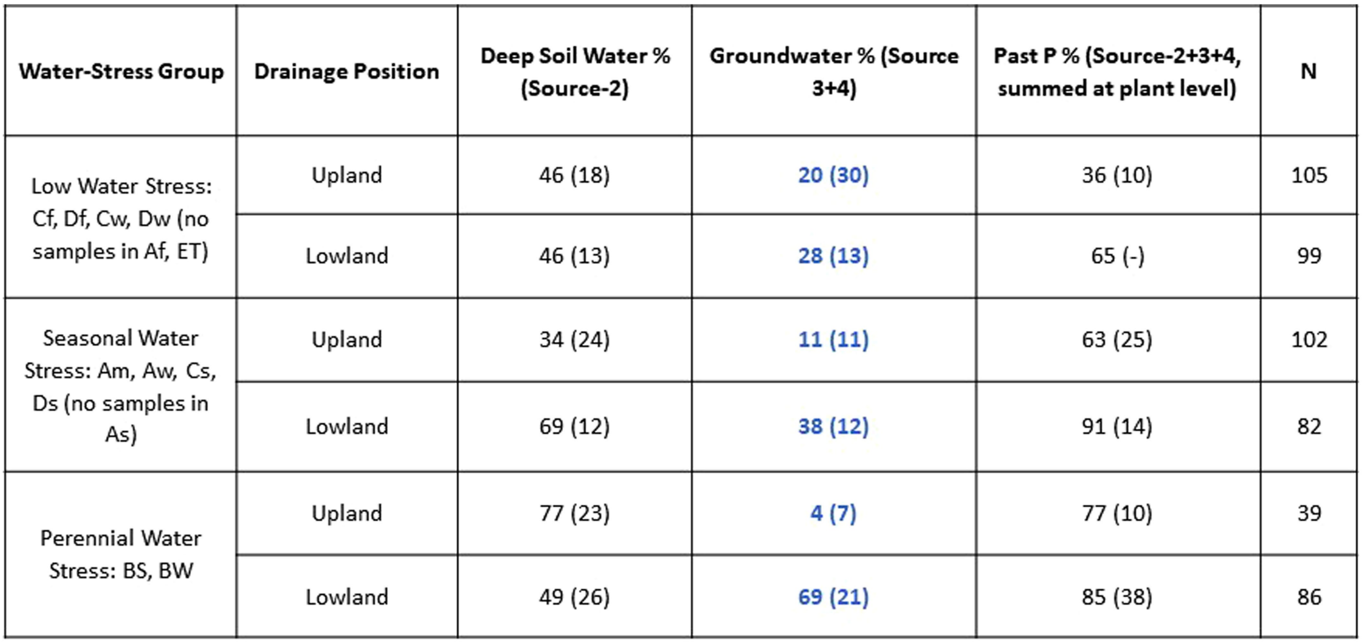
Extended Data Table 4 | Isotope-based estimate of vegetation use of past precipitation (past P) (as % xylem water) averaged over each climatic water stress class, with propagated error in parentheses



Rank	Water-Stress Group	Fractional Plant Use of Source-2 (Deep Soil Water), %			Fractional Plant Use of Source-3 and 4 (Groundwater), %			Total Use of Past P (Source-2+3+4, summed at plant level), %			N
		Dry Periods	Wet Periods	Growing Season	Dry Periods	Wet Periods	Growing Season	Dry Periods	Wet Periods	Growing Season	
1	Cs (temperate, summer dry)	53 (18)	25 (20)	51 (24)	37 (12)	22 (13)	45 (10)	89 (16)	47 (17)	71 (18)	68
2	BS (arid steppe)	58 (20)	37 (11)	28 (24)	52 (21)	43 (16)	46 (23)	85 (35)		64 (43)	**73**
3	Ds (cool, summer dry)	35 (24)	21 (14)	29 (22)				79 (32)		54 (32)	11
4	Am (tropical, monsoonal)	72 (12)	24 (8)	53 (8)	9 (6)	5 (6)	7 (6)	76 (12)	25 (8)	57 (8)	29
5	BW (arid desert)	80 (30)	58 (23)	48 (23)	67 (5)	7 (5)	45 (23)	73 (9)	99 (8)	67 (23)	52
6	Aw (tropical, winter dry)	27 (31)	2 (-)		44 (14)	31 (12)	30 (14)	60 (39)	5 (-)		**76**
7	Cw (temperate, winter dry)	52 (10)	28 (11)	35 (13)	13 (19)	8 (14)	12 (18)	44 (-)		46 (20)	59
8	Cf (temperate, fully humid)	44 (19)	18 (5)	30 (15)	30 (18)	3 (3)	24 (20)			22 (11)	90
9	Dw (cool, winter dry)	34 (11)		19 (8)	11 (23)			43 (10)		18 (8)	29
10	Df (cool, fully humid)			36 (16)			26 (9)			26 (9)	26
11	As (tropical, summer dry)										0
12	Af (tropical, fully humid)										0
13	ET (polar, tundra)										0
	All Groups	47 (19)	30 (15)	39 (19)	39 (14)	25 (12)	37 (18)	77 (22)	33 (11)	**50 (21)**	513

Coloured fonts are mentioned in the main text.

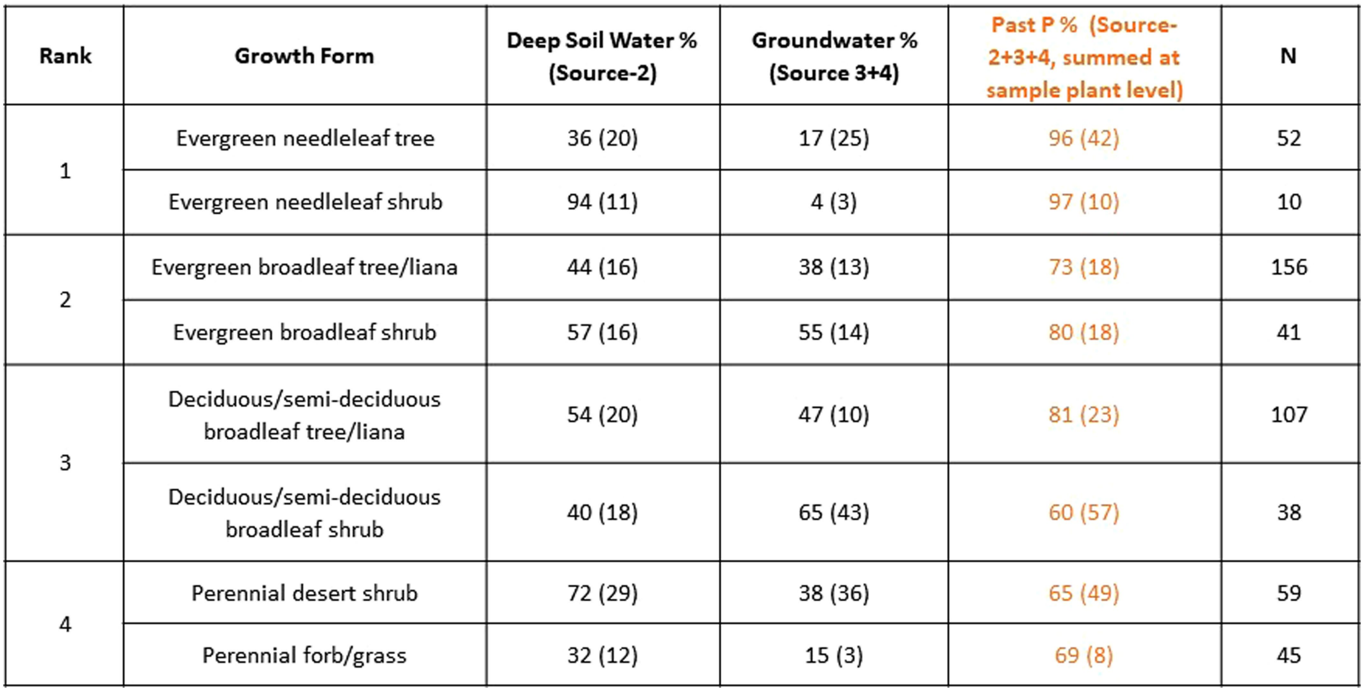
Extended Data Table 5 | Isotope-based estimates of dry period vegetation use of past precipitation along drainage gradient, with propagated error in parentheses



Water-Stress Group	Drainage Position	Deep Soil Water % (Source-2)	Groundwater % (Source 3+4)	Past P % (Source-2+3+4, summed at plant level)	N
Low Water Stress: Cf, Df, Cw, Dw (no samples in Af, ET)	Upland	46 (18)	20 (30)	36 (10)	105
	Lowland	46 (13)	28 (13)	65 (-)	99
Seasonal Water Stress: Am, Aw, Cs, Ds (no samples in As)	Upland	34 (24)	11 (11)	63 (25)	102
	Lowland	69 (12)	38 (12)	91 (14)	82
Perennial Water Stress: BS, BW	Upland	77 (23)	4 (7)	77 (10)	39
	Lowland	49 (26)	69 (21)	85 (38)	86

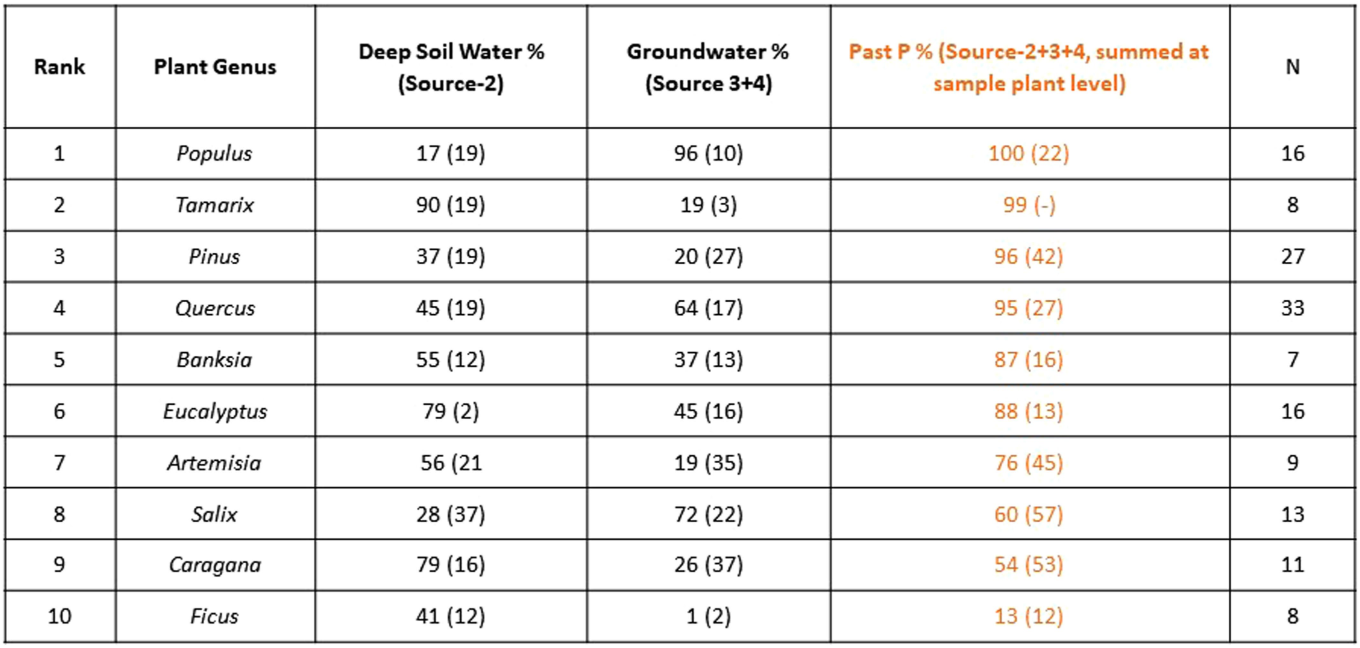
Colored fonts are values mentioned in the main text.

Extended Data Table 6 | Isotope-based estimates of dry season vegetation use of past precipitation for eight growth forms with >10 observations, with propagated error term in parentheses; they are loosely ranked by the total plant use of past precipitation (orange)



Rank	Growth Form	Deep Soil Water % (Source-2)	Groundwater % (Source 3+4)	Past P % (Source-2+3+4, summed at sample plant level)	N
1	Evergreen needleleaf tree	36 (20)	17 (25)	96 (42)	52
	Evergreen needleleaf shrub	94 (11)	4 (3)	97 (10)	10
2	Evergreen broadleaf tree/liana	44 (16)	38 (13)	73 (18)	156
	Evergreen broadleaf shrub	57 (16)	55 (14)	80 (18)	41
3	Deciduous/semi-deciduous broadleaf tree/liana	54 (20)	47 (10)	81 (23)	107
	Deciduous/semi-deciduous broadleaf shrub	40 (18)	65 (43)	60 (57)	38
4	Perennial desert shrub	72 (29)	38 (36)	65 (49)	59
	Perennial forb/grass	32 (12)	15 (3)	69 (8)	45

Extended Data Table 7 | Isotope-based estimates of dry season vegetation use of past precipitation for the 10 best sampled genera



Rank	Plant Genus	Deep Soil Water % (Source-2)	Groundwater % (Source 3+4)	Past P % (Source-2+3+4, summed at sample plant level)	N
1	*Populus*	17 (19)	96 (10)	100 (22)	16
2	*Tamarix*	90 (19)	19 (3)	99 (-)	8
3	*Pinus*	37 (19)	20 (27)	96 (42)	27
4	*Quercus*	45 (19)	64 (17)	95 (27)	33
5	*Banksia*	55 (12)	37 (13)	87 (16)	7
6	*Eucalyptus*	79 (2)	45 (16)	88 (13)	16
7	*Artemisia*	56 (21	19 (35)	76 (45)	9
8	*Salix*	28 (37)	72 (22)	60 (57)	13
9	*Caragana*	79 (16)	26 (37)	54 (53)	11
10	*Ficus*	41 (12)	1 (2)	13 (12)	8

Ranking is based on total use of past precipitation (orange).

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Reporting Summary

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Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐	A description of all covariates tested
☒	☐	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	The software Graph Data Extractor beta version (https://sourceforge.net/projects/graphdataextrac/) is used to extract relative contributions of plant water source from published literature.
Data analysis	Microsoft Office 2019 Excel is used for calculating means and standard deviations. Our custom inverse model code, written in FORTRAN, is uploaded to github at: https://github.com/gmiguez/MMF-HYDROMODEL. We followed USGS MODFLOW-2000 River package to model river-groundwater exchange.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

All model input data are generated by government and research agencies, and all are in the public domain. Links to download them are given in Table S2.
Modeled monthly transpiration and source contributions (Source-1, 2, 3, 4) for each continent and month can be downloaded at the following public repository via ftp:
http://thredds-gfnl.usc.es/thredds/catalog/DATA_TRANSPSOURCES/catalog.html

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	The study estimates the space and time origin of the soil water that is taken up by plants, at the global and monthly scales, using a global high-resolution inverse model, corroborated by isotope-based estimates compiled from published literature
Research sample	The study compiled published literature reports of plant water sources. The references (data sources) are given in the Extended Data as an Excel sheet.
Sampling strategy	We did not perform any sampling of plants and soils, but compiled the data from published studies. We performed an exhaustive search for published studies and found 110 studies with sufficient information to translate the depth of plant water uptake into the four water sources defined in this study. The sample size is small in humid climates, because most isotope studies are performed in dry climates where drought is a concern for ecosystem functions. The sparse field studies and the bias toward dry climates and wealthy nations are a key reason behind our use of global inverse modeling, which shed lights on places and times where no field work has been conducted.
Data collection	Coauthor Ying Fan compiled the data from the literature. A Web of Science Search yielded ~300 papers on using isotopes to identify plant water sources, but only 110 of these studies reported precipitation history and isotopes, soil soil moisture dynamics etc. for us to infer infiltration depth, so that we could convert depth to timing of precipitation that filled the soil water stores. We recorded the data and calculated the means and standard deviation using Excel (Office 2019), with each sampling site recorded as a separate entrance, resulting in 515 site or individual plant and its source water contributions.
Timing and spatial scale	In isotope data collection, we included all studies we could find in the published literature, which span the time frame from 1992 to 2020. Sampling time and frequency varied across the 110 studies, and most reported snap shots of wet or dry periods, some reported monthly means. Spatially, measurements of plant xylem water isotopes are of individual plants, often averaged across duplicate samples. We recorded the sample size in the Excel data sheet (column F) uploaded to Nature. In our inverse modeling, the model is run at hourly steps over 10 years (2004-2013) and at a global grid of 30" (~1km), providing spatially complete coverage of all continents and continuously for 10 years. We only saved and analyzed monthly model outputs because monthly data are manageable (available to download at a public repository) and yet fine enough to capture seasonal dynamics, which are our primary focus.
Data exclusions	Many isotope studies are excluded from our compilation, because they do not provide the essential information for us to infer the age of the soil water (current month or past).
Reproducibility	All the isotope studies from which we extracted our data have been published, so it is easy to check the compilation. Our inverse model is driven by publicly available climate and land data. We have uploaded the code to Github and model output to a public data repository, with links provided under Code Availability and Data Availability Statements.
Randomization	We did not randomly select studies to include, because we wanted to include all published studies that could shed light on the origin of plant water sources. The data we compiled from the literature were binned into climate types according to the international standard (the classic Koppen-Gieger climate classification). We binned the data into climate (testing hypothesis-2) and growth form and genera (testing hypothesis-3 and 4). Growth form and species likely covary with climate, but the small sample size does not allow us to control for each other, as mentioned in the manuscript where we can only draw tentative conclusions. This problem can only be solved in time as more and more field studies are conducted and reported.
Blinding	Blinding is not relevant because we wanted to include all published studies that could shed light on the origin of plant water sources. Such studies are very few and hence precious.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging