

1 **SAPFLUXNET: towards a global database of sap flow measurements**

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14 Keywords: drought, evapotranspiration, functional traits, plant water use, plant

15 hydraulics, sap flux, transpiration

## 16 **Abstract**

17 Plant transpiration is the main evaporative flux from terrestrial ecosystems, it controls  
18 land surface energy balance, determines catchment hydrological responses and  
19 influences regional and global climate. Transpiration regulation by plants is a key  
20 (and still not completely understood) process that underlies vegetation drought  
21 responses and land evaporative fluxes under global change scenarios.

22 Thermometric methods of sap flow measurement have now been widely used to  
23 quantify whole-plant and stand transpiration in forests, shrublands and orchards  
24 around the world. A large body of research has applied sap flow methods to analyse  
25 seasonal and diurnal patterns of transpiration and to quantify their responses to  
26 hydroclimatic variability, but syntheses of sap flow data at regional to global scales  
27 are extremely rare. Here we present the SAPFLUXNET initiative, aimed at building  
28 the first global database of plant-level sap flow measurements. A preliminary  
29 metadata survey launched in December 2015, showed an encouraging response by  
30 the sap flow community, with sap flow datasets from field studies representing >160  
31 species and >120 globally distributed sites. The main goal of SAPFLUXNET is to  
32 analyse the ecological factors driving plant- and stand-level transpiration.

33 SAPFLUXNET will open promising research avenues at an unprecedented global  
34 scope, namely: (i) exploring the spatiotemporal variability of plant transpiration and  
35 its relationship with plant and stand attributes (ii) summarising physiological  
36 regulation of transpiration by means of few water use traits, usable for land surface  
37 models, (iii) improving our understanding of the coordination between gas exchange  
38 and plant-level traits (e.g. hydraulics) and (iv) analysing the ecological factors  
39 controlling stand transpiration and evapotranspiration partitioning. Finally,

40 SAPFLUXNET can provide a benchmark to test models of physiological controls of  
41 transpiration, contributing to improve the accuracy of individual water stress  
42 responses, a key element to obtain robust predictions of vegetation responses to  
43 climate change.

44 Keywords: drought, evapotranspiration, functional traits, plant water use, plant  
45 hydraulics, sap flux, transpiration

46 *Plant transpiration is a key component of land evaporative fluxes, but it is hard to*  
47 *measure*

48 Plant transpiration is the main evaporative flux from terrestrial ecosystems  
49 (Schlesinger and Jasechko 2014), it controls land surface energy balance,  
50 determines catchment hydrological responses and influences regional and global  
51 climate (Bonan 2008). Because of the central role played by their water economy,  
52 plants adjust physiologically and structurally to maintain their hydraulic integrity and  
53 metabolic function under drought at various time and organisational scales (Maseda  
54 and Fernández 2006). These adjustments determine how plants regulate  
55 transpiration under fluctuating conditions of water supply and demand, resulting in  
56 multiple water use strategies within and across ecosystems. The diversity of water  
57 use strategies underlie plant drought responses, and these responses are major  
58 drivers of demographic rates (McDowell et al. 2008) community dynamics  
59 (Silvertown et al. 2015) and ecosystem function. Transpiration regulation by plants is  
60 thus a key (and still not completely understood) process that underlies vegetation  
61 drought responses (McDowell et al. 2013) and land evaporative fluxes (Oishi et al.  
62 2010, Miralles et al. 2011) under global change scenarios.

63 The measurement of plant transpiration and its drivers is deeply rooted in the history  
64 of quantitative experiments in plant biology but most of the experimental techniques  
65 developed before the 1950's were intrusive and unsuitable for the investigation of the  
66 driving factors of transpiration of living plants, especially under field conditions  
67 (Wullschleger et al. 1998). The advent of gas exchange systems allowed the  
68 development of automated cuvettes to measure transpiration from leaves to whole

69 plants, but the upscaling of leaf-to-plant transpiration is highly labour-intensive and  
70 error-prone, while chamber-based measurements of whole-plant transpiration are  
71 logistically demanding can and alter canopy microclimate (Goulden and Field 1994).  
72 Micrometeorological techniques, stand or catchment water balances and remote  
73 sensing approaches provide evapotranspiration estimates, but neither of these  
74 methods is suitable to study water use strategies of individual plants across the  
75 entire spatiotemporal domain.

76 *Sap flow methods: development, limitations and contribution to progress in*  
77 *understanding tree and ecosystem physiology*

78 Thermometric methods of sap flow measurement were devised during the 1930s and  
79 refined in the late 1950s (Marshall 1958). The main methodological families were  
80 already established by the mid-1980s and many improvements and new derivations  
81 have continued to appear (Čermák et al. 2004, Vandegehuchte and Steppe 2013  
82 and references therein). Sap flow methods measure either total sap flow through a  
83 plant's organ or sap flux density, the flow rate per unit conducting area  
84 (Vandegehuchte and Steppe 2013). They use pulsed or continuous heating and track  
85 temperature changes caused by convective heat transport by moving sap in different  
86 plant organs along the transpiration pathway (Goldstein et al. 1998, Burgess et al.  
87 2000). Given the easy replication and automation of sap flow probes, they have been  
88 widely used on main, woody stems to quantify tree and stand transpiration (Granier  
89 et al. 1996).

90 Each of the sap flow methods has distinct advantages and methodological  
91 constraints. No single method is able to measure the entire range of sap flow rates

92 and all of them are subject to one or more of the following issues (Vandegehuchte  
93 and Steppe 2013): incomplete contact of the probe with the sapwood, natural  
94 temperature gradients, the need for species-specific calibrations and parameters,  
95 uncertainty in baseline flow estimates, wounding effects and sensor drift. These  
96 potential artefacts may be aggravated by within-method differences in sensor design  
97 among manufacturers and laboratories (Lu et al. 2004). Unsurprisingly, validation  
98 studies have raised concerns about the potential biases incurred by most sap flow  
99 methods (Steppe et al. 2010). Additional uncertainty results from upscaling from  
100 sensors to trees and to stands (Oren et al. 1998, Čermák et al. 2004). Nevertheless,  
101 all methods yield reasonable temporal patterns of plant transpiration and sap flow-  
102 derived transpiration has often compared well with independent measurements  
103 (McCulloh et al. 2007) and with evapotranspiration at larger scales (Wilson et al.  
104 2001).

105 Sap flow methods have greatly contributed to addressing fundamental questions of  
106 (mostly woody) plant and ecosystem physiology, such as age/height- (Hubbard et al.  
107 1999) and drought-related variations in the water transport capacity of plants  
108 (Cochard et al. 1996), the mechanisms of stem water storage dynamics (Goldstein et  
109 al. 1998) or foliar water uptake (Burgess and Dawson 2004). Sap flow methods have  
110 also been successfully applied to study broader ecological questions, such as the  
111 effects of tree diversity on ecosystem functioning (Forrester et al. 2010). At a more  
112 applied level, sap flow is frequently measured in studies designed to guide  
113 silvicultural or agronomic practices (Jones 2004, Aranda et al. 2012). A large body of  
114 research has applied sap flow methods to analyse seasonal and diurnal patterns of  
115 transpiration and canopy (stomatal) conductance ( $G_s$ ) (Phillips and Oren 1998) and

116 to quantify their responses to hydroclimatic variability.

117 *The time is ripe for a global database of sap flow measurements: the SAPFLUXNET*  
118 *initiative*

119 Sap flow probes are relatively affordable and easy to deploy in the field, but they  
120 have logistic requirements that preclude the long-term maintenance of multiple  
121 experimental sites across broad ecological gradients. Data syntheses of sap flow (or  
122  $G_s$ ) responses to hydroclimatic factors across species have either focused on  
123 responses to single variables (Oren et al. 1999) or they have been limited to a few  
124 closely-related species (Duursma et al. 2008), likely reflecting limitations in data  
125 availability in relatively homogeneous and comparable formats. Indeed, a recent  
126 global synthesis of sap flow focusing on pine stands' response to variation in leaf  
127 area index, soil and climate variables, required digitizing published data (Tor-ngern et  
128 al. 2016), introducing additional, unnecessary errors. Only a few studies have  
129 analysed responses of sap-flow and/or  $G_s$  across a diverse group of tree species  
130 (Granier et al. 2000) or along wide climatic gradients within a species (Poyatos et al.  
131 2007). Other quantitative syntheses have typically analysed maximum values of sap  
132 flow or  $G_s$ , either measured during short periods or retrieved from published sources.  
133 These studies have mostly dealt with how maximum sap flow rates vary with  
134 allometry (Meinzer et al. 2005), plant hydraulics (Manzoni et al. 2013) or wood traits  
135 (Kallarackal et al. 2013).

136 Increasing data sharing and reuse promotes progress in ecology by extending the  
137 value of data beyond individual studies (Wolkovich et al. 2012). Global and regional  
138 networks of biosphere-atmosphere carbon and water exchange curate regional and

139 global datasets, improve data interoperability and enable collaborations and data  
140 syntheses (Papale et al. 2012). Recent methodological progress in data  
141 management, database design (Boden et al. 2013), and open-source software tools  
142 have occurred in concert with the increasing availability of global databases.  
143 Functional and ecosystem ecologists are already producing global syntheses on  
144 vegetation controls of water balance and on plant's drought vulnerability (Choat et al.  
145 2012, Williams et al. 2012). However, the sap flow community has not yet fully  
146 embraced this challenge; for instance, sap flow datasets are mostly absent from the  
147 main data repositories for ecological or Earth system sciences (one dataset for  
148 canopy transpiration in try-db.org; one dataset, with peak values only, in  
149 datadryad.org; none in pangaea.de, re3data.org or zenodo.org; all repositories  
150 accessed May 2016).

151 The sap flow-related literature is already substantial: a Scopus search ("sap flow"  
152 OR "sapflow" OR "sap flux" OR "sapflux" in title, abstract or keywords) returned  
153 >2500 papers, whose keywords included the scientific names of >250 plant species,  
154 according to The Plant List (The Plant List (2013). Version 1.1. ;  
155 <http://www.theplantlist.org/>). These figures likely overestimate the number of potential  
156 data sources, but they nevertheless suggest that an ecologically relevant compilation  
157 is feasible. We searched the title, abstract and keywords of these papers to retrieve  
158 the sap flow method(s) used in each paper, and we show that the heat dissipation  
159 method (Granier 1985) is the most popular, by far (Figure 1). The SAPFLUXNET  
160 initiative (<http://sapfluxnet.creaf.cat/>) is building the first global database of plant-level  
161 sap flow measurements (obtained using thermometric methods) to analyse the  
162 environmental and physiological factors driving tree- and stand-level transpiration. A

163 preliminary metadata survey launched in December 2015, showed an encouraging  
164 response by the sap flow community. Potentially contributed sap flow datasets from  
165 field studies represent >160 species and >120 globally distributed sites (Figure 2).  
166 We have now started the data collection stage, and we welcome processed sap flow  
167 datasets measured at the stem or whole-plant level (but not at the branch level),  
168 under field conditions and at sub-daily intervals. Please see the SAPFLUXNET wiki  
169 <https://github.com/sapfluxnet/sapfluxnet-public/wiki> for further details on minimum  
170 requirements for sap flow, environmental and ancillary data. Our ultimate goal is that,  
171 by the end of the project (September 2018), a first version of the SAPFLUXNET  
172 database is made available to data contributors. After an embargo period, the  
173 database will be made publicly available to the scientific community.

174 Building a harmonized database from highly heterogeneous data sources is a  
175 challenging endeavour. We have designed a semi-automated, reproducible and  
176 version-controlled, data ingestion process using the tools provided by the R  
177 environment (e.g. R language for computing and statistics, interactive R Markdown  
178 documents and Shiny apps). Data incorporation to the server and initial data quality  
179 control (timestamp and units standardization, species and geographic coordinates  
180 validation, gap quantification) is automatically performed by R functions (Figure 3).

181 SAPFLUXNET will compile, curate and disseminate processed data. Since sap flow  
182 measurements are affected by a substantial methodological variability sap flow time  
183 series in SAPFLUXNET are documented with metadata on sensor characteristics,  
184 data processing and upscaling procedures, provided by data contributors. For  
185 example, we specify whether species-specific calibrations (Steppe et al. 2010) or

186 natural gradient corrections (Do and Rocheteau 2002) have been applied to the raw  
187 data. These metadata will allow us to account for variability caused by  
188 methodological issues in joint analyses using the database. SAPFLUXNET will thus  
189 allow a first quantification of the impacts of methodological variability on sap flow  
190 measurements across a large number of species. We expect that these analyses will  
191 foster the development of standardized protocols within the sap flow community, as a  
192 prerequisite towards a fully coherent database similarly to what FLUXNET has  
193 achieved for ecosystem-level CO<sub>2</sub> and water fluxes (Papale et al. 2012). There have  
194 been recent advances in this direction with the dissemination of code for robust,  
195 semi-automatic flux baselining for heat dissipation probes (Oishi et al. 2016) and for  
196 generalised integration of radial variation of sap flow in the scaling to whole-tree  
197 water use (Berdanier et al. 2016).

198 *Unravelling the ecological drivers of plant transpiration to understand drought*  
199 *vulnerability and ecosystem physiology*

200 The SAPFLUXNET initiative will provide opportunities to improve our understanding  
201 of the ecological determinants of plant water use and drought responses. It will allow  
202 describing how annually or seasonally-integrated plant transpiration vary across  
203 biomes, plant functional types or taxonomic groups. SAPFLUXNET will open  
204 promising research avenues at an unprecedented global scope, namely: (I) exploring  
205 the spatiotemporal variability of plant transpiration and its relationship with plant and  
206 stand attributes (ii) summarising physiological regulation of transpiration by means of  
207 water use traits, representing maximum water transport rates and sensitivity to  
208 environmental factors, usable for land surface models, (iii) improving our

209 understanding of the coordination between gas exchange and plant-level traits (e.g.  
210 hydraulics) and (iv) analysing the ecological factors controlling stand transpiration  
211 and evapotranspiration partitioning.

212 SAPFLUXNET will allow the first analyses of biogeographical and climate-driven  
213 patterns of plant transpiration. The variation in transpiration with water availability will  
214 be assessed using probabilistic, multiscale drought indices (Vicente-Serrano et al.  
215 2010), which include drought responses at multiple temporal scales and allow  
216 comparisons across ecosystems with contrasting water availability. Moreover,  
217 SAPFLUXNET will extend scaling relationships between sap flux density and plant  
218 size and hydraulic architecture (e.g. sapwood area, leaf area), to test for functional  
219 convergence across functional types, genera or environmental gradients (Zeppel  
220 2013). As stand-level hydraulic adjustments (Whitehead et al. 1984) covary with  
221 plant water availability, a relevant question will be to assess how these scaling  
222 relationships vary with stand structure (e.g. basal area, density, canopy height).

223 One of the main goals of SAPFLUXNET will be to summarise physiological  
224 regulation of transpiration by means of few water use traits. For example, semi-  
225 empirical responses of sap flow (or canopy conductance) to radiation, vapour  
226 pressure deficit and soil moisture can be embedded in dynamic, hierarchical  
227 Bayesian models, which can deal with observation, process and parameter  
228 uncertainties enabling the analysis of heterogeneous sap flow datasets (Ward et al.  
229 2013). Water use traits derived from these models represent complex  
230 ecophysiological strategies as emerging relationships, such as the trade-off between  
231 maximum stomatal conductance and sensitivity to vapour pressure deficit, which

232 arises from stomatal limitation of xylem embolism (Oren et al. 1999). This trade-off,  
233 provides a benchmark to investigate variation in physiological regulation of  
234 transpiration across biomes, climates (Poyatos et al. 2007), wood anatomy types  
235 (Meinzer et al. 2013) or taxonomic groups (Johnson et al. 2012). Moreover,  
236 physiological responses to soil moisture, radiation and atmospheric turbulence are  
237 virtually unexplored at regional to global scales.

238 Coordination of canopy gas exchange and whole-plant hydraulics has long been  
239 proposed (Meinzer 2002), but only recently have global syntheses of hydraulic traits  
240 started to provide a broader picture of the ecological patterns and the multiple facets  
241 of drought tolerance in plants. Whole-plant water use traits derived from  
242 SAPFLUXNET will help complete the worldwide spectrum of hydraulic strategies  
243 defined by gas exchange and water potential regulation (Martínez-Vilalta et al.  
244 2014), hydraulic safety margins (Choat et al. 2012), capacitance (Meinzer et al.  
245 2009) and leaf water relations (Bartlett et al. 2012). Combining global sap flow data  
246 with on-site water potentials will also simplify the parameterisation of whole-plant  
247 transpiration models (Sperry and Love 2015).

248 At the ecosystem level, SAPFLUXNET can provide globally-distributed values of  
249 seasonally- and annually-aggregated stand transpiration, which will improve our  
250 understanding of the biophysical controls of vegetation-atmosphere fluxes (Köstner  
251 2001) and will help constrain the estimates of transpiration-to-evapotranspiration  
252 ratios (Schlesinger and Jasechko 2014). SAPFLUXNET can help to link plant  
253 functional traits with ecosystem water and carbon fluxes (Reichstein et al. 2014).  
254 Finally, SAPFLUXNET can provide a benchmark to test algorithms of physiological

255 controls of transpiration embedded in process-based models (Williams et al. 2001),  
256 contributing to improve the accuracy of individual water stress responses, a key  
257 element to obtain robust predictions of vegetation responses to climate change  
258 (Levine et al. 2015).

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## References

- Aranda I, Forner A, Cuesta B, Valladares F (2012) Species-specific water use by forest tree species: From the tree to the stand. *Agric Water Manag* 114:67–77.
- Baker JM, Van Bavel CHM (1987) Measurement of mass flow of water in the stems of herbaceous plants. *Plant Cell Environ* 10:777–782.
- Bartlett MK, Scoffoni C, Sack L (2012) The determinants of leaf turgor loss point and prediction of drought tolerance of species and biomes: a global meta-analysis. *Ecol Lett* 15:393–405.
- Berdanier AB, Miniati CF, Clark JS (2016) Predictive models for radial sap flux variation in coniferous, diffuse-porous and ring-porous temperate trees. *Tree Physiol*, <http://dx.doi.org/10.1093/treephys/tpw027>.
- Boden TA, Krassovski M, Yang B (2013) The AmeriFlux data activity and data system: an evolving collection of data management techniques, tools, products and services. *Geosci Instrum Methods Data Syst* 2:165–176.
- Bonan GB (2008) Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. *Science* 320:1444–1449.
- Burgess SSO, Adams MA, Bleby TM (2000) Measurement of sap flow in roots of woody plants: a commentary. *Tree Physiol* 20:909–913.
- Burgess SSO, Dawson TE (2004) The contribution of fog to the water relations of *Sequoia sempervirens* (D. Don): foliar uptake and prevention of dehydration. *Plant Cell Environ* 27:1023–1034.
- Čermák J, Kučera J, Nadezhdina N (2004) Sap flow measurements with some thermodynamic methods, flow integration within trees and scaling up from sample trees to entire forest stands. *Trees* 18:529–546.

- Choat B, Jansen S, Brodribb TJ, Cochard H, Delzon S, Bhaskar R, Bucci SJ, Feild TS, Gleason SM, Hacke UG, Jacobsen AL, Lens F, Maherali H, Martínez-Vilalta J, Mayr S, Mencuccini M, Mitchell PJ, Nardini A, Pittermann J, Pratt RB, Sperry JS, Westoby M, Wright IJ, Zanne AE (2012) Global convergence in the vulnerability of forests to drought. *Nature* 491:752–755.
- Cochard H, Bréda N, Granier A (1996) Whole tree hydraulic conductance and water loss regulation in *Quercus* during drought: evidence for stomatal control of embolism? *Ann Sci For* 53:197–206.
- Do F, Rocheteau A (2002) Influence of natural temperature gradients on measurements of xylem sap flow with thermal dissipation probes. 1. Field observations and possible remedies. *Tree Physiol* 22:641–648.
- Duursma R, Kolari P, Perämäki M, Nikinmaa E, Hari P, Delzon S, Loustau D, Ilvesniemi H, Pumpanen J, Mäkelä A (2008) Predicting the decline in daily maximum transpiration rate of two pine stands during drought based on constant minimum leaf water potential and plant hydraulic conductance. *Tree Physiol* 28:265–276.
- Forrester DI, Theiveyanathan S, Collopy JJ, Marcar NE (2010) Enhanced water use efficiency in a mixed *Eucalyptus globulus* and *Acacia mearnsii* plantation. *For Ecol Manag* 259:1761–1770.
- Goldstein G, Andrade JL, Meinzer FC, Holbrook NM, Cavelier J, Jackson P, Celis A (1998) Stem water storage and diurnal patterns of water use in tropical forest canopy trees. *Plant Cell Environ* 21:397–406.
- Goulden ML, Field CB (1994) Three methods for monitoring the gas exchange of individual tree canopies: ventilated-chamber, sap-flow and Penman-Monteith measurements on evergreen oaks. *Funct Ecol* 8:125–135.
- 264 Granier A (1985) Une nouvelle méthode pour la mesure du flux de sève brute dans le  
265 tronc des arbres. *Annales des Sciences Forestières* 42:193–200.
- Granier A, Biron P, Bréda N, Pontailier JY, Saugier B (1996) Transpiration of trees and forest stands: short and long-term monitoring using sapflow methods. *Glob Change Biol* 2:265–274.
- Granier A, Loustau D, Bréda N (2000) A generic model of forest canopy conductance dependent on climate soil water availability and leaf area index. *Ann Sci For* 57:755–765.
- Hubbard RM, Bond BJ, Ryan MG (1999) Evidence that hydraulic conductance limits photosynthesis in old *Pinus ponderosa* trees. *Tree Physiol* 19:165–172.

- Johnson DM, McCulloh KA, Woodruff DR, Meinzer FC (2012) Hydraulic safety margins and embolism reversal in stems and leaves: Why are conifers and angiosperms so different? *Plant Sci* 195:48–53.
- Jones HG (2004) Irrigation scheduling: advantages and pitfalls of plant-based methods. *J Exp Bot* 55:2427–2436.
- Kallarackal J, Otieno DO, Reineking B, Jung E-Y, Schmidt MWT, Granier A, Tenhunen JD (2013) Functional convergence in water use of trees from different geographical regions: a meta-analysis. *Trees* 27:787–799.
- Köstner B (2001) Evaporation and transpiration from forests in Central Europe - Relevance of patch-level studies for spatial scaling. *Meteorol Atmospheric Phys* 76:69–82361.
- Levine NM, Zhang K, Longo M, Baccini A, Phillips OL, Lewis SL, Alvarez-Dávila E, Andrade ACS de, Brienen RJW, Erwin TL, Feldpausch TR, Mendoza ALM, Vargas PN, Prieto A, Silva-Espejo JE, Malhi Y, Moorcroft PR (2015) Ecosystem heterogeneity determines the ecological resilience of the Amazon to climate change. *Proc Natl Acad Sci* 113:793–797.
- Lu P, Urban L, Ping Z (2004) Granier's thermal dissipation probe (TDP) method for measuring sap flow in trees: theory and practice. *Acta Bot Sin* 46:631–646.
- Manzoni S, Vico G, Katul G, Palmroth S, Jackson RB, Porporato A (2013) Hydraulic limits on maximum plant transpiration and the emergence of the safety–efficiency trade-off. *New Phytol* 198:169–178.
- Marshall DC (1958) Measurement of sap flow in conifers by heat transport. *Plant Physiol* 33:385–396.
- Martínez-Vilalta J, Poyatos R, Aguadé D, Retana J, Mencuccini M (2014) A new look at water transport regulation in plants. *New Phytol* 204:105–115.
- Maseda PH, Fernández RJ (2006) Stay wet or else: three ways in which plants can adjust hydraulically to their environment. *J Exp Bot* 57:3963.
- McCulloh KA, Winter K, Meinzer FC, Garcia M, Aranda J, Lachenbruch B (2007) A comparison of daily water use estimates derived from constant-heat sap-flow probe values and gravimetric measurements in pot-grown saplings. *Tree Physiol* 27:1355–1360.
- McDowell NG, Fisher RA, Xu C, Domec JC, Hölttä T, Mackay DS, Sperry JS, Boutz A, Dickman L, Gehres N, Limousin JM, Macalady A, Martínez-Vilalta J, Mencuccini M, Plaut JA, Ogée J, Pangle RE, Rasse DP, Ryan MG, Sevanto S, Waring RH, Williams AP, Yopez EA, Pockman WT (2013) Evaluating theories of drought-induced vegetation mortality using a multimodel–experiment framework. *New Phytol* 200:304–321.

- McDowell N, Pockman WT, Allen CD, Breshears DD, Cobb N, Kolb T, Plaut J, Sperry J, West A, Williams DG, Yepez EA (2008) Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? *New Phytol* 178:719–739.
- Meinzer FC (2002) Co-ordination of vapour and liquid phase water transport properties in plants. *Plant Cell Env* 25:265–274.
- Meinzer FC, Bond BJ, Warren JM, Woodruff DR (2005) Does water transport scale universally with tree size? *Funct Ecol* 19:558–565.
- Meinzer FC, Johnson DM, Lachenbruch B, McCulloh KA, Woodruff DR (2009) Xylem hydraulic safety margins in woody plants: coordination of stomatal control of xylem tension with hydraulic capacitance. *Funct Ecol* 23:922–930.
- Meinzer FC, Woodruff DR, Eissenstat DM, Lin HS, Adams TS, McCulloh KA (2013) Above- and belowground controls on water use by trees of different wood types in an eastern US deciduous forest. *Tree Physiol* 33:345–356.
- Miralles DG, De Jeu RAM, Gash JH, Holmes TRH, Dolman AJ (2011) Magnitude and variability of land evaporation and its components at the global scale. *Hydrol Earth Syst Sci* 15:967–981.
- Oishi AC, Oren R, Novick KA, Palmroth S, Katul GG (2010) Interannual Invariability of Forest Evapotranspiration and Its Consequence to Water Flow Downstream. *Ecosystems* 13:421–436.
- 266 Oishi AC, Hawthorne DA, Oren R (2016) Baseline: An open-source, interactive tool  
267 for processing sap flux data from thermal dissipation probes. *SoftwareX*.  
268 <http://dx.doi.org/10.1016/j.softx.2016.07.003>.
- Oren R, Phillips N, Katul G, Ewers BE, Pataki DE (1998) Scaling xylem sap flux and soil water balance and calculating variance: a method for partitioning water flux in forests. *Ann Sci For* 55:191–216.
- Oren R, Sperry JS, Katul GG, Pataki DE, Ewers BE, Phillips N, Schafer KVR (1999) Survey and synthesis of intra- and interspecific variation in stomatal sensitivity to vapour pressure deficit. *Plant Cell Environ* 22:1515–1526.
- Papale D, Agarwal DA, Baldocchi D, Cook RB, Fisher JB, Ingen C van (2012) Database Maintenance, Data Sharing Policy, Collaboration. In: Aubinet M, Vesala T, Papale D (eds) *Eddy Covariance*. Springer Netherlands, pp 399–424.
- Phillips N, Oren R (1998) A comparison of daily representations of canopy conductance based on two conditional time averaging-methods and the dependence of daily conductance on environmental factors. *Ann Sci For* 55:217–235.

- Poyatos R, Martínez-Vilalta J, Čermák J, Ceulemans R, Granier A, Irvine J, Köstner B, Lagergren F, Meiresonne L, Nadezhdina N, Zimmermann R, Llorens P, Mencuccini M (2007) Plasticity in hydraulic architecture of Scots pine across Eurasia. *Oecologia* 153:245–259.
- Reichstein M, Bahn M, Mahecha MD, Kattge J, Baldocchi DD (2014) Linking plant and ecosystem functional biogeography. *Proc Natl Acad Sci* 111:13697–13702.
- Schlesinger WH, Jasechko S (2014) Transpiration in the global water cycle. *Agric For Meteorol* 189–190:115–117.
- Silvertown J, Araya Y, Gowing D (2015) Hydrological niches in terrestrial plant communities: a review. *J Ecol* 103:93–108.
- Sperry JS, Love DM (2015) What plant hydraulics can tell us about responses to climate-change droughts. *New Phytol* 207:14–27.
- Steppe K, De Pauw DJW, Doody TM, Teskey RO (2010) A comparison of sap flux density using thermal dissipation, heat pulse velocity and heat field deformation methods. *Agric For Meteorol* 150:1046–1056.
- 269 Tor-ngern P, Oren R, Oishi AC, Uebelherr JM, Palmroth S, Tarvainen L, Ottosson-  
270 Löfvenius M, Linder S, Domec J-C, Näsholm T (2016) Ecophysiological  
271 variation of transpiration of pine forests: synthesis of new and published  
272 results. *Ecol App*, <http://dx.doi.org/10.1002/eap.1423>.
- Vandegehuchte MW, Steppe K (2013) Sap-flux density measurement methods: working principles and applicability. *Funct Plant Biol* 40:213–223.
- Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *J Clim* 23:1696–1718.
- Ward EJ, Oren R, Bell DM, Clark JS, McCarthy HR, Kim H-S, Domec J-C (2013) The effects of elevated CO<sub>2</sub> and nitrogen fertilization on stomatal conductance estimated from 11 years of scaled sap flux measurements at Duke FACE. *Tree Physiol* 33:135–151.
- Whitehead D, Jarvis PG, Waring RH (1984) Stomatal conductance, transpiration, and resistance to water uptake in a *Pinus sylvestris* spacing experiment. *Can J For Res* 14:692–700.

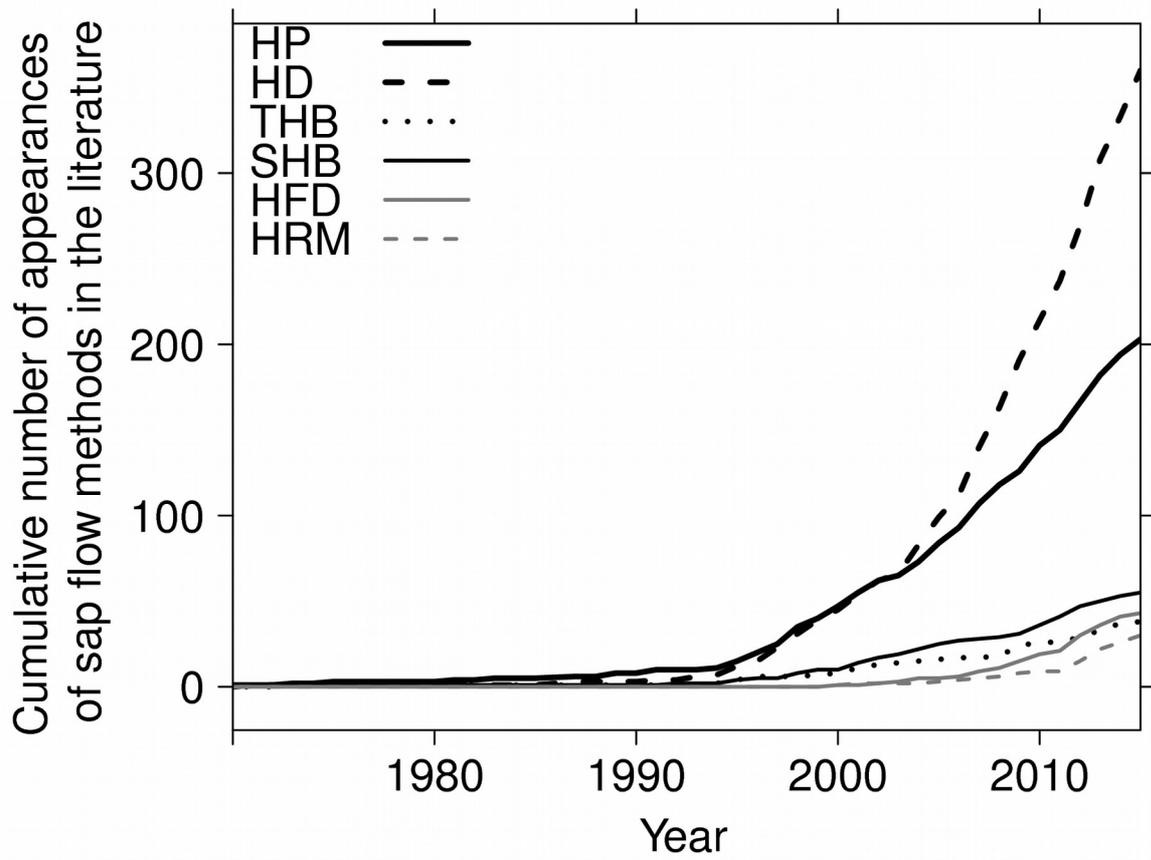
- Williams M, Bond BJ, Ryan MG (2001) Evaluating different soil and plant hydraulic constraints on tree function using a model and sap flow data from ponderosa pine. *Plant Cell Env* 24:679–690.
- Williams CA, Reichstein M, Buchmann N, Baldocchi D, Beer C, Schwalm C, Wohlfahrt G, Hasler N, Bernhofer C, Foken T, Papale D, Schymanski S, Schaefer K (2012) Climate and vegetation controls on the surface water balance: Synthesis of evapotranspiration measured across a global network of flux towers. *Water Resour Res* 48:W06523.
- Wilson KB, Hanson PJ, Mulholland PJ, Baldocchi DD, Wullschleger SD (2001) A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance. *Agric For Meteorol* 106:153–168.
- Wolkovich EM, Regetz J, O'Connor MI (2012) Advances in global change research require open science by individual researchers. *Glob Change Biol* 18:2102–2110.
- Wullschleger SD, Meinzer FC, Vertessy RA (1998) A review of whole-plant water use studies in trees. *Tree Physiol* 18:499–512.
- Zeppel M (2013) Convergence of tree water use and hydraulic architecture in water-limited regions: a review and synthesis. *Ecohydrology* 6:889–900.

273 **Figure captions**

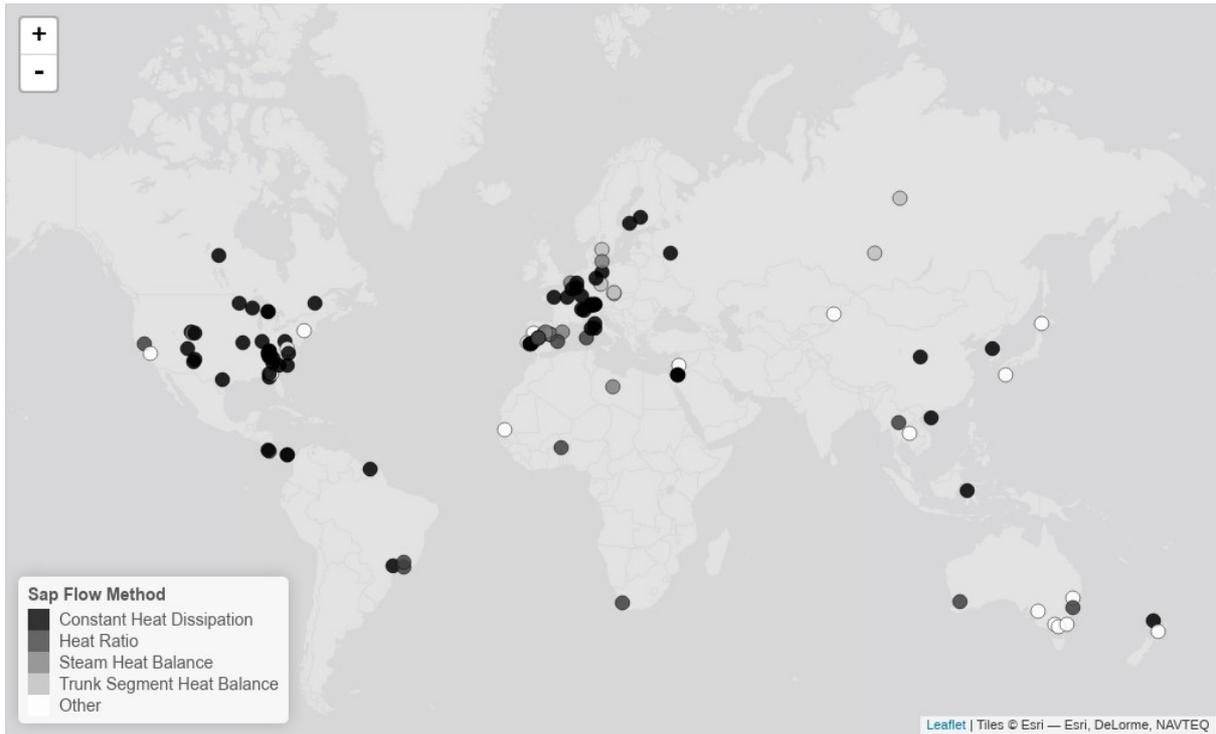
274 Figure 1. Cumulative count of appearances of different sap flow methods in a  
275 Scopus search of sap flow-related literature ("sap flow" OR "sapflow" OR "sap  
276 flux" OR "sapflux" in title, abstract or keywords). Note that counts represent  
277 individual appearances of each method, not papers (e.g. a paper can have multiple  
278 methods). HP: heat pulse methods, include Compensation Heat Pulse, Tmax  
279 Method, Calibrated Average Gradient and Sapflow+; HD; Heat Dissipation; THB:  
280 Tissue Heat Balance; SHB: Stem Heat Balance; HFD: Heat Field Deformation; HRM:  
281 Heat Ratio Method.

282 Figure 2. Geographic distribution of potential sap flow data sources, coded by sap  
283 flow method, based on a preliminary survey. An interactive summary of this  
284 preliminary survey, with further information on the growth condition of the stand, the  
285 number of species and trees can be found at  
286 [http://sapfluxnet.creaf.cat/shiny/preliminary\\_dashboard/](http://sapfluxnet.creaf.cat/shiny/preliminary_dashboard/).

287 Figure 3. Data flow from reception to production of level 1 datasets. Initial data and  
288 metadata quality control is encapsulated in a R package under continuous  
289 development. This semi-automated procedure generates interactive QC reports that  
290 are shared with data contributors to resolve any issues with the data. All the  
291 individual steps in this procedure and any manual changes on the datasets are  
292 traceable because they are logged in structured text files. Beyond Level 1, data  
293 processing is under implementation, as depicted by discontinuous lines.



294 Figure 1.



295 Figure 2

