



Universiteit
Leiden
The Netherlands

Functional xylem anatomy: intra and interspecific variation in stems of herbaceous and woody species

Chacon Dória, L.

Citation

Chacon Dória, L. (2019, October 9). *Functional xylem anatomy: intra and interspecific variation in stems of herbaceous and woody species*. Retrieved from <https://hdl.handle.net/1887/79255>

Version: Publisher's Version

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/79255>

Note: To cite this publication please use the final published version (if applicable).

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/79255> holds various files of this Leiden University dissertation.

Author: Chacon Dória L.

Title: Functional xylem anatomy: intra and interspecific variation in stems of herbaceous and woody species

Issue Date: 2019-10-09

REFERENCES

- Ackerly D. 2004. Functional strategies of chaparral shrubs in relation to seasonal water deficit and disturbance. *Ecological Monographs* 74: 25 - 44.
- Adams HD, Zeppel MJB, Anderegg WRL, Hartmann H, Landhausser SM, Tissue DT, et al. 2017. A multi-species synthesis of physiological mechanisms in drought-induced tree mortality. *Nature, Ecology & Evolution* 1: 1285 - 1291.
- Ahmad HB, Lens F, Capdeville G, Burlett R, Lamarque LJ, Delzon S. 2018. Intraspecific variation in embolism resistance and stem anatomy across four sunflower (*Helianthus annuus* L.) accessions. *Physiologia Plantarum* 163: 59 - 72.
- Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, et al. 2010. A global overview of drought and heat- induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* 259: 660 - 684.
- Aloni R, Zimmermann MH. 1983. The control of vessel size and density along the plant axis. *Differentiation* 24: 203 - 208.
- Aloni R. 2015. Ecophysiological implications of vascular differentiation and plant evolution. *Trees-Structure and Function* 29: 1 - 16.
- Alves ES, Angyalossy-Alfonso V. 2000. Ecological trends in the wood anatomy of some Brazilian species. 1. Growth rings and vessels. *IAWA Journal* 21: 3 - 30.
- Alves ES, Angyalossy-Alfonso V. 2002. Ecological trends in the wood anatomy of some Brazilian species. 2 Axial parenchyma, rays and fibers. *IAWA Journal* 23: 391 - 418.
- Anderegg WRL, Berry JA, Smith DD, Sperry JS, Anderegg LDL, Field C. 2012. The roles of hydraulic and carbon stress in a widespread climate-induced forest die-off. *Proceedings of the National Academy of Science USA* 109: 233-237.
- Anderegg LDL, Anderegg WRL, Berry JA. 2013. Not all droughts are created equal: translating meteorological drought into woody plant mortality. *Tree Physiology* 33: 701 - 712.
- Anderegg WRL. 2015. Spatial and temporal variation in plant hydraulic traits and their relevance for climate change impacts on vegetation. *New Phytologist* 205: 1008 - 1014.
- Anderegg WRL, Meinzer FC. 2015. Wood anatomy and plant hydraulics in a changing climate. In: Hacke U (Ed.), *Functional and Ecological Xylem Anatomy*. Springer International Publishing Switzerland, pp: 235 - 253.
- Anderegg WRL, Klein T, Bartlett M, Sack L, Pellegrini AFA, Choat B, et al. 2016. Meta-analysis reveals that hydraulic traits explain cross-species patterns of drought-induced tree mortality across the globe. *Proceedings of the National Academy of Science USA* 113: 5024 - 5029.
- Andrade-Lima D. 1981. The Caatingas dominium. *Brazilian Journal of Botany* 4: 149 - 163.

- Anfodillo T, Petit G, Crivellaro A. 2013. Axial conduit widening in woody species: a still neglected anatomical pattern. IAWA Journal 34: 352 - 364.
- Arechavaleta M, Rodriguez S, Zurita N García A. 2010. Lista de especies silvestres de Canarias: hongos, plantas y animales terrestres. Gobierno de Canarias, Tenerife, pp. 579
- Arens K. 1958. Consideracoes sobre as causas do xeromorfismo foliar. Boletim da Faculdade de Filosofia Ciências e Letras da USP 224: 25 - 56.
- Arens K, Ferri MG, Coutinho LM. 1958. Papel do fator nutricional na economia d'água de plantas do cerrado. Revista de Biologia 1: 313 - 324.
- Awad H, Herbette S, Brunel N, Tixier A, Pilate G, Cochard H, et al. 2012. No trade-off between hydraulic and mechanical properties in several transgenic poplars modified for lignin metabolism. Environmental and Experimental Botany 77: 185 - 195.
- Baas P. 1976. Some functional and adaptive aspects of vessel member morphology. Leiden Botanical Series 3: 157 - 181.
- Baas P, Werker E, Fahn A. 1983. Some ecological trends in vessel characters. IAWA Bulletin 4: 141 - 159.
- Baas P, Carlquist S. 1985. A comparison of the ecological wood anatomy of the floras of Southern California and Israel. Iawa Journal 6: 349 - 353.
- Baas P, Schweingruber FH. 1987. Ecological trends in the wood anatomy of trees, shrubs and climbers from Europe. IAWA Bulletin New Series. 8: 245 - 274.
- Baas P, Ewers FW, Davis SD, Wheeler EA. 2004. Evolution of xylem physiology. In: Hemsley AR, Poole I. (Eds.), The Evolution of Plant Physiology: From Whole Plant to Ecosystems. Elsevier Academic, Amsterdam, pp: 273 - 295.
- Bailey IW, Tupper WW. 1918. Size variation in tracheary cells: a comparison between the secondary xylems of vascular cryptogams, gymnosperms and angiosperms. Proceedings of the American Academy of Arts and Sciences 54: 149 - 204.
- Baldwin BG, Sanderson MJ. 1998. Age and rate of diversification of the Hawaiian silversword alliance (Compositae). Proceedings of the National Academy of Science USA 95: 9402 - 9406.
- Barigah TS, Charrier O, Douris M, Bonhomme M, Herbette S, Améglio T, et al. 2013. Water stress-induced xylem hydraulic failure is a causal factor of tree mortality in beech and poplar. Annals of Botany 112: 1431 - 1437.
- Barnard DM, Meinzer FC, Lachenbruch B, McCulloh KA, Johnson DM, Woodruff DR. 2011. Climate-related trends in sapwood biophysical properties in two conifers: avoidance of hydraulic dysfunction through coordinated adjustments in xylem efficiency, safety and capacitance. Plant, Cell & Environment 34: 643 - 654.
- Bittencourt PRL, Pereira L, Oliveira RS. 2016. On xylem hydraulic efficiencies, wood space-use and the safety - efficiency tradeoff. New Phytologist 211: 1152 - 1155.
- Blackman CJ, Brodribb TJ, Jordan GJ. 2012. Leaf hydraulic vulnerability influences species' bioclimatic limits in a diverse group of woody angiosperms. Oecologia 168: 1 - 10.
- Böhle UR, Hilger HH, Martin WF. 1996. Island colonization and evolution of the insular woody habit in *Echium* L. (Boraginaceae). Proceedings of the National Academy of Sciences of the United States of America 93: 11740 - 11745.
- Borchert R, Pockman WT. 2005. Water storage capacitance and xylem tension in isolated branches of temperate and tropical trees. Tree Physiology 25: 457 - 466.

- Bosio F, Soffiatti P, Torres-Boeger MR. 2010. Ecological wood anatomy of *Miconia sellowiana* (Melastomataceae) in three vegetation types of Paraná State, Brazil. IAWA Journal 31: 179 - 190.
- Bouche PF, Larter M, Domec JC, Burlett R, Gasson P, Jansen S, et al. 2014. A broad survey of xylem hydraulic safety and efficiency in conifers. Journal of Experimental Botany 65: 4419 - 4431.
- Brodersen C, McElrone A, Choat B, Matthews M, Shackel K. 2010. The dynamics of embolism repair in xylem: in vivo visualizations using high-resolution computed tomography. Plant Physiology 154: 1088 - 1095.
- Brodersen CR, McElrone AJ. 2013. Maintenance of xylem network transport capacity: a review of embolism repair in vascular plants. Frontiers in Plant Science 108: 1 - 11.
- Brodersen CR, McElrone AJ, Choat B, Lee EF, Shackel KA, Matthews MA. 2013. In vivo visualizations of drought-induced embolism spread in *Vitis vinifera*. Plant Physiology 161: 1820 - 1829.
- Brodersen CR, Knipfer T, McElrone A. 2018. In vivo visualization of the final stages of xylem vessel refilling in grapevine (*Vitis vinifera*) stems. New Phytologist 217: 117 - 126.
- Brodribb TJ, Field TS. 2000. Stem hydraulic supply is linked to leaf photosynthetic capacity: evidence from New Caledonian and Tasmanian rainforests. Plant, Cell & Environment 23: 1381 - 1388.
- Brodribb TJ, Hill RS. 2000. Increases in water potential gradient reduce xylem conductivity in whole plants. Evidence from a low-pressure conductivity method. Plant Physiology 123: 1021 - 1028.
- Brodribb TJ, Holbrook NM. 2005. Water stress deforms tracheids peripheral to the leaf vein of a tropical conifer. Plant Physiology 173: 1139 - 1146.
- Brodribb TJ. 2009. Xylem hydraulic physiology: the functional backbone of terrestrial plant productivity. Plant Science 177: 245 - 251.
- Brodribb TJ, Cochard H. 2009. Hydraulic failure defines the recovery and point of death in water-stressed conifers. Plant Physiology 149: 575 - 584.
- Brodribb TJ, Bowman D, Nichols S, Delzon S, Burlett R. 2010. Xylem function and growth rate interact to determine recovery rates after exposure to extreme water deficit. New Phytologist 188: 533 - 542.
- Brodribb TJ, Pittermann J, Coomes DA. 2012. Elegance versus speed: examining the competition between conifer and angiosperm trees. International Journal of Plant Sciences 173: 673 - 694.
- Brodribb TJ, Skelton RP, McAdam SAM, Bienaimé D, Lucani CJ, Marmottant P. 2016. Visual quantification of embolism reveals leaf vulnerability to hydraulic failure. New Phytologist 209: 1403 - 1409.
- Brodribb TJ. 2017. Progressing from 'functional' to mechanistic traits. New Phytologist 215: 9 - 11.
- Brookshire ENJ, Weaver T. 2015. Long-term decline in grassland productivity driven by increasing dryness. Nature communications 6: 7148.
- Bucci SJ, Scholz FG, Goldstein G, Meinzer FC, Sternberg LDSL. 2003. Dynamic changes in hydraulic conductivity in petioles of two savanna tree species: factors and mechanisms contributing to the refilling of embolized vessels. Plant, Cell & Environment 26: 1633 - 1645.
- Burgert I, Bernasconi A, Eckstein D. 1999. Evidence for the strength function of rays in living trees. Holz als Roh-und Werkstoff 57: 397 - 399.
- Burgert I, Eckstein D. 2001. The tensile strength of isolated wood rays of beech (*Fagus sylvatica* L.) and its significance for the biomechanics of living trees. Trees 15: 168 - 170.
- Burgess SO, Pittermann J, Dawson TE. 2006. Hydraulic efficiency and safety of branch xylem increases with height in *Sequoia sempervirens* (D.Don) crowns. Plant, Cell & Environment 29: 229 - 239.

Cardoso AA, Brodribb TJ, Lucani CJ, DaMatta FM, McAdam SAM. 2018. Coordinated plasticity maintains hydraulic safety in sunflower leaves. *Plant, Cell & Environment* 41: 2567 - 2576.

Carlquist S. 1966. Wood anatomy of Compositae: a summary, with comments on factors controlling wood evolution. *Aliso* 6: 25 - 44.

Carlquist S. 1974. Insular woodiness. In: *Island Biology*, Columbia University Press, New York, pp: 350 - 428.

Carlquist S. 1975. Ecological strategies of xylem evolution. University of California Press, Berkeley.

Carlquist S. 1977. Ecological factors in wood evolution, a floristic approach. *American Journal of Botany* 6: 887 - 896.

Carlquist S. 1980. Further concepts in ecological wood anatomy, with comments on recent work in wood anatomy and evolution. *Aliso* 9: 499 - 553.

Carlquist S. 1982. Wood anatomy of *Illicium* (Illiciaceae). Phylogenetical, ecological and functional interpretations. *American Journal of Botany* 69: 1587 - 1598.

Carlquist S. 1984. Vessel grouping in Dicotyledon wood: significance and relationship to imperforate tracheary elements. *Aliso* 10: 505 - 525.

Carlquist S. 1985. Vasicentric tracheids as a drought survival mechanism in the woody flora of southern California and similar regions; review of vasicentric tracheids. *Aliso* 11: 37 - 68.

Carlquist S, Hoekman DA. 1985. Ecological wood anatomy of the woody southern Californian flora. *IAWA Bulletin* 6: 319 - 347.

Carlquist S. 1988. Tracheids dimorphism: a new pathway in evolution of imperforate tracheary elements. *Aliso* 12: 103 - 118.

Carlquist S. 2001. Comparative Wood Anatomy. Systematic, Ecological and Evolutionary Aspects of Dicotyledon Wood, 2nd ed. Springer, Santa Barbara.

Carlquist S. 2012. How wood evolves: a new synthesis. *Botany* 90: 901 - 940.

Challinor AJ, Ewert F, Arnold S, Simelton E, Fraser E. 2009. Crops and climate change: progress, trends, and challenges in simulating impacts and informing adaptation. *Journal of Experimental Botany* 60: 2775 - 2789.

Chave J, Muller-Landau HC, Baker TR, Easdale TA, Steege H ter, Webb CO. 2006. Regional and phylogenetic variation of wood density across 2456 neotropical tree species. *Ecology Application* 16: 2356 - 2367.

Chave J, Coomes D, Jansen S, Lewis SL, Swenson NG, Zanne AE. 2009. Towards a worldwide wood economics spectrum. *Ecology Letters* 12: 351 - 366.

Chevan A, Sutherland M. 1991. Hierarchical partitioning. *American Statistical Association* 45: 90 - 96.

Choat B, Ball MC, Luly JG, Holtum JAM. 2005. Hydraulic architecture of deciduous and evergreen dry rainforest tree species from north-eastern Australia. *Trees* 19: 305 - 311.

Choat B, Brodie Tw, Cobb AR, Zwieniecki MA, Holbrook NM. 2006. Direct measurements of intervessel pit membrane hydraulic resistance in two angiosperm tree species. *American Journal of Botany* 93: 993 - 1000.

Choat B, Sack L, Holbrook NM. 2007. Diversity of hydraulic traits in nine *Cordia* species growing in tropical forests with contrasting precipitation. *New Phytologist* 175: 686 - 698.

- Choat B, Cobb AR, Jansen S. 2008. Structure and function of bordered pits: new discoveries and impacts on whole-plant hydraulic function. *New Phytologist* 177: 608 - 626.
- Choat B, Drayton WM, Brodersen C, Matthews MA, Shackel KA, Wada H. *et al.* 2010. Measurement of vulnerability to water stress-induced cavitation in grapevine: a comparison of four techniques applied to a long-vesseled species. *Plant, Cell & Environment* 33: 1502 - 1412.
- Choat B, Jansen S, Brodribb TJ, Cochard H, Delzon S, Bhaskar R, *et al.* 2012. Global convergence in the vulnerability of forests to drought. *Nature* 491: 752 - 755.
- Ciais O, Reichstein M, Viovy N, Granier A, Ogée J, Allard V, *et al.* 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature* 437: 529 - 533.
- Cochard H. 2002. A technique for measuring xylem hydraulic conductance under high negative pressures. *Plant, Cell & Environment* 25: 815-819.
- Cochard H, Nardini A, Coll L. 2004. Hydraulic architecture of the leaf blades: where is the main resistance? *Plant, Cell & Environment* 27: 1257 - 1267.
- Cochard H, Gaelle D, Bodet C, Tharwat I, Poirier M, Ameglio T. 2005. Evaluation of a new centrifuge technique for rapid generation of xylem vulnerability curves. *Physiologia Plantarum* 124: 410 - 418.
- Cochard H. 2006. Cavitation in trees. *Comptes Rendus Physique* 7: 1018 - 1026.
- Cochard H, Barigah T, Kleinhentz M, Eshel A. 2008. Is xylem cavitation resistance a relevant criterion for screening drought resistance among *Prunus* species? *Journal of Plant Physiology* 165: 976 - 982.
- Cochard H, Herbette S, Barigah T, Badel E, Ennajeh M, Vilagrosa A. 2010. Does sample length influence the shape of xylem embolism vulnerability curves? A test with the Cavitron spinning technique. *Plant, Cell & Environment* 33: 1543 - 1552.
- Cochard H, Badel E, Herbette S, Delzon S, Choat B, Jansen S. 2013. Methods for measuring plant vulnerability to cavitation: a critical review. *Journal of Experimental Botany* 64: 4779 - 4791.
- Corcuera L, Cochard H, Gil-Pelegrin E, Notivol E. 2011. Phenotypic plasticity in mesic populations of *Pinus pinaster* improves resistance to xylem embolism (P_{50}) under severe drought. *Trees* 25: 1033 - 1042.
- Coutinho LM. 1983. Aspectos ecológicos da saúva no cerrado – a saúva, as queimadas, e sua possível relação na ciclagem de nutrientes. *Boletim de Zoologia* 8: 1 - 9.
- Coutinho LM. 2002. O bioma do cerrado. In: Klein AL (Ed.), *Eugen Warming e o Cerrado Brasileiro*. UNESP, Imprensa Oficial do Estado, São Paulo, pp: 77 - 92.
- Crawley MJ. 2007. *The R Book*. Chichester: John Wiley & Sons Ltd.
- Dai AG. 2013. Increasing drought under global warming in observations and models. *Nature Climate Change* 3: 52 - 58.
- Darwin C. 1859. *On the origin of species by means of natural selection (reprint of 1st ed. 1950)*. J. Murray, London.
- Davis SD, Sperry JS, Hacke UG. 1999. The relationship between xylem conduit diameter and cavitation caused by freezing. *American Journal of Botany* 86: 1367 - 1372.
- del-Arco M, Pérez-de-Paz PL, Acebes JR, González-Mancebo JM, Reyes-Betancort J, Bermejo JA, *et al.* 2006. Bioclimatology and climatophilous vegetation of Tenerife (Canary Islands). *Annales Botanici Fennici* 43: 167 - 192.

- Delzon S, Cochard H. 2014. Recent advances in tree hydraulics highlight the ecological significance of the hydraulic safety margin. *New Phytologist* 203: 355 - 358.
- Dixon HH, Joly J. 1894. On the ascent of sap. *Philosophical Transactions of the Royal Society London* 186: 563-576.
- Dixon HH. 1914. *Transpiration and the Ascent of Sap*. Macmillan and Co. Ltd., London.
- Domec J-C, Lachenbruch B, Meinzer FC, Woodruff DR, Warren JM, McCulloh KA. 2008. Maximum height in a conifer is associated with conflicting requirements for xylem design. *Proceedings of National Academic Science USA* 33: 12069 - 12074.
- Dória LC, Podadera DS, Batalha, MA, Lima, RS, Marcati, CR. 2016. Do woody plants of the Caatinga show a higher degree of xeromorphism than in the Cerrado? *Flora* 224: 244 - 251.
- Dória LC, Podadera DS, del Arco M, Chauvin T, Smets E, Delzon S, et al. 2018. Insular woody daisies (*Argyranthemum*, Asteraceae) are more resistant to drought-induced hydraulic failure than their herbaceous relatives. *Functional Ecology* 32: 1467 - 1478.
- Dória LC, Meijs C, Podadera DS, del Arco M, Smets E, Delzon S, et al. 2019. Embolism resistance in stems of herbaceous Brassicaceae and Asteraceae is linked with differences in woodiness and precipitation. *Annals of Botany* 124: 1 - 14.
- Doyle JA. 2012. Molecular and fossil evidence on the origin of angiosperms. *Annual Review of Earth and Planetary Sciences* 40: 301 - 326.
- Dulin, MW, Kirchoff BK. 2010. Paedomorphosis, secondary woodiness and insular woodiness in plants. *Botanical review* 76: 405 - 490.
- Eckblad JW. 1991. How many samples should be taken. *Journal of Biological Sciences* 41: 346 - 348.
- Engelbrecht BMJ, Comita LS, Condit R, Kursar TA, Tyree MT, Turner BL, et al. 2007. Drought sensitivity shapes species distribution patterns in tropical forests. *Nature* 447: 80 - 82.
- Esau K. 1965. *Plant Anatomy*. 2nd Edition, John Wiley, New York.
- Evert RF. 2006. *Esau's Plant Anatomy: Meristems, Cells, and Tissues of the Plant Body: Their Structure, Function, and Development*. 3rd Edition. John Wiley & Sons, Inc.
- Ewers FW, Fisher JB, Chiu S. 1990. A survey of vessel dimensions in stems of tropical lianas and other growth forms. *Bauhinia* 84: 544 - 552.
- Fan ZX, Cao KF, Becker P. 2009. Axial and radial variations in xylem anatomy of angiosperm and conifer trees in Yunnan, China. *IAWA Journal* 30: 1 - 13.
- Fichot R, Barigah TS, Chamaillard S, LE Thiec D, Laurans F, Cochard H, et al. 2010. Common trade-offs between xylem resistance to cavitation and other physiological traits do not hold among unrelated *Populus deltoids* × *Populus nigra* hybrids. *Plant, Cell & Environment* 33: 1553 - 1568.
- Francisco-Ortega J, Crawford DJ, Santos-Guerra A, Jansen RK. 1997. Origin and evolution of *Argyranthemum* (Asteraceae: Anthemidae) in Macaronesia. In Givnish TJ, Sytsma KJ (Eds.), *Molecular evolution and adaptive radiation*. Cambridge University Press, Cambridge, pp: 407 - 431.
- Franklin GL. 1945. Preparation of thin sections of synthetic resins and wood-resins composites, and a new macerating method for wood. *Nature* 155: 51.
- Freese F. 1967. *Elementary Statistical Methods for Foresters*, USDA Forest Service, Agriculture Handbook 317, Washington.
- Givnish TJ. 1998. Adaptive plant evolution on islands: classical patterns, molecular data, new insights. In: Grant PR (Ed.), *Evolution on Islands*, Oxford University Press, Oxford, pp: 281-304.

- Gleason SM, Butler DW, Ziemska K, Waryszak P, Westoby M. 2012. Stem xylem conductivity is key to plant water balance across Australian angiosperm species. *Functional ecology* 26: 343 - 356.
- Gleason SM, Westoby M, Jansen S. Choat B, Hacke UG, Pratt RB, et al. 2016a. Weak tradeoff between xylem safety and xylem-specific hydraulic efficiency across the world's woody plant species. *New Phytologist* 209: 123 - 136.
- Gleason SM, Westoby M, Jansen S, Choat B, Brodribb TJ, Chochard H, et al. 2016b. On research priorities to advance understanding of the safety-efficiency trade off in xylem. *New Phytologist* 211: 1156 - 1158.
- Hacke UG, Sperry JS, Pockman WT, Davis SD, McCulloh KA. 2001a. Trends in wood density and structure are linked to prevention of xylem implosion by negative pressure. *Oecologia* 126: 457 - 461.
- Hacke UG, Stiller V, Sperry JS, Pittermann J, McCulloh KA. 2001b. Cavitation fatigue. Embolism and refilling cycles can weaken the cavitation resistance of xylem. *Plant Physiology* 125: 779 - 786.
- Hacke UG, Sperry JS. 2003. Limits to xylem refilling under negative pressure in *Laurus nobilis* and *Acer negundo*. *Plant, Cell & Environment* 26: 303 - 311.
- Hacke UG, Sperry JS, Pitterman J. 2004. Analysis of circular bordered pit function. II. Gymnosperm tracheids with torus-margo pit membranes. *American Journal of Botany* 91: 386 - 400.
- Hacke UG, Sperry JS, Wheeler JK, Castro L. 2006. Scaling of angiosperm xylem structure with safety and efficiency. *Tree Physiology* 26: 689 - 701.
- Hacke UG, Jansen S. 2009. Embolism resistance of three boreal conifer species varies with pit structure. *New Phytologist* 182: 675 - 686.
- Hacke UG, Spicer R, Schreiber SG, Plavcová L. 2017. An ecophysiological and developmental perspective on variation in vessel diameter. *Plant Cell & Environment* 40: 831 - 845.
- Hamann TD, Smets E, Lens F. 2011. A comparison of paraffin and resin-based techniques used in bark anatomy. *Taxon* 60: 841 - 851.
- Hanhijarvi A, Wahl P, Rasanen J, Silvennoinen R. 2003. Observation of development of microcracks on wood surface caused by drying stresses. *Holzforschung* 57: 561 - 565.
- Hartmann H. 2011. Will a 385 million year-struggle for light become a struggle for water and for carbon? – How trees may cope with more frequent climate change-type drought events. *Global Change Biology* 17: 642 - 655.
- Hoffman WA, Marchin RM, Abit P, Lau LO. 2011. Hydraulic failure and tree dieback are associated with high wood density in a temperate forest under extreme drought. *Global Change Biology* 17: 2731 - 2742.
- Holbrook MN. 1995. Stem water storage. In: Gardner BL (Ed.), *Plant stems*. Academic Press, New York, pp: 151 - 174.
- Holste EK, Jerke MJ, Matzner SL. 2006. Long-term acclimatization of hydraulic properties, xylem conduit size, wall strength and cavitation resistance in *Phaseolus vulgaris* in response to different environmental effects. *Plant, Cell & Environment* 29: 836 - 843.
- Hölttä T, Vesala T, Perämäki M, Nikinmaa E. 2006. Refilling of embolised conduits as a consequence of 'Münch water' circulation. *Functional Plant Biology* 33: 949 - 959.
- Hölttä T, Mencuccini, M, Nikinmaa, E. 2011. A carbon cost-gain model explains the observed patterns of xylem safety and efficiency. *Plant, Cell & Environment* 34: 1819 - 1834.
- Humphries CJ. 1976. A revision of the Macaronesian genus *Argyranthemum* Webb ex Schultz-Bip. (Compositae-Anthemideae). *Bulletin of the British Museum (Natural History) Botany* 5: 147 - 240.

IAWA Committee. 1989. IAWA list of microscopic features for hardwood identification. IAWA Bulletin 10: 219 - 332.

IBGE [Instituto Brasileiro de Geografia e Estatística]. 2012. Manual técnico da vegetação brasileira. IBGE, Rio de Janeiro.

Ilic J. 1999. Shrinkage-related degrade and its association with some physical properties in *Eucalyptus regnans* F. Muell. Wood Science and Technology 33: 425 - 437.

Iqbal M. 1995. The cambial derivatives. Schweizerbart Science Publishers, Stuttgart.

Jacobsen AL, Ewers FW, Pratt RB, Paddock WA, Davis D. 2005. Do xylem fibers affect vessel cavitation resistance? Plant Physiology 139: 546 - 556.

Jacobsen AL, Pratt RB, Davis SD, Ewers FW. 2007. Cavitation resistance and seasonal hydraulics differ among three arid Californian plant communities. Plant, Cell & Environment 30: 1599 - 1609.

Jacobsen AL, Pratt RB, Tobin MF, Hacke UG, Ewers FW. 2012. A global analysis of xylem vessel length in woody plants. American Journal of Botany 99: 1583 - 1591.

Jacobsen AL, Pratt RB. 2018. Going with the flow: structural determinants of vascular tissue transport efficiency and safety. Plant, Cell & Environment 41: 2715 - 2717.

James S, Meinzer F, Goldstein G, et al. 2003. Axial and radial water transport and internal water storage in tropical forest canopy trees. Oecologia 134: 37 - 45.

Jansen J, Baas P, Gasson P, Lens F, Smets E. 2004. Variation in xylem structure from tropics to tundra: evidence from vestured pits. Proceedings of the National Academy Sciences USA 101: 8833 - 8837.

Jansen S, Choat B, Pletsers A. 2009. Morphological variation of intervessel pit membranes and implications to xylem function in angiosperms. American Journal of Botany 96: 409 - 419.

Jansen S, Schenk HJ. 2015. On the ascent of sap in the presence of bubbles. American Journal of Botany 102: 1561 - 1563.

Johansen DA. 1940. Plant Microtechnique. McGraw Hill, New York.

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 Sciences 195: 48 - 53.

Karnovsky MJ. 1965. A formaldehyde - glutaraldehyde fixative of high osmolality for use in electron microscopy. Journal of Cell Biology 27: 137 - 138.

Kattge J, Diaz S, Lavorel S, Prentices IC, Leadley P, Bonisch G, et al. 2011. TRY – a global database of plant traits. Global Change Biology 17: 2905 - 2935.

Kidner C, Groover A, Thomas D, Emelianova K, Soliz-Gamboa C, Lens F. 2016. First steps in studying the origins of secondary woodiness in *Begonia* (Begoniaceae): combining anatomy, phylogenetics, and stem transcriptomics. Biological Journal of the Linnean Society 117: 121 - 138.

Kitin P, Voelker SL, Meinzer FC, Beeckman H, Strauss SH, Lachenbruch B. 2010. Tyloses and phenolic deposits in xylem vessels impede water transport in low-lignin transgenic poplars: A study by cryo-fluorescence microscopy. Plant Physiology 154: 887 - 898.

Knipfer T, Brodersen CR, Zedan A, Kluepfel DA, McElrone AJ. 2015. Patterns of drought-induced embolism formation and spread in living walnut saplings visualized using X-ray microtomography. Tree Physiology 35: 744 - 755.

Kochian LV. 1995. Cellular mechanisms of aluminum toxicity and resistance in plants. Annual Review of Plant Physiology and Plant Molecular Biology 46: 237 - 260.

- Kokacinar F, Sage RF. 2003. Photosynthetic pathway alters xylem structure and hydraulic function in herbaceous plants. *Plant, Cell & Environment* 26: 2015 - 2026.
- Kolb KJ, Sperry JS. 1999. Differences in drought adaptation between subspecies of Sagebrush (*Artemisia tridentata*). *Ecology* 7: 2373 - 2384.
- Koch GW, Sillett SC, Jennings GM, Davis SD. 2004. The limits to tree height. *Nature* 428: 851 - 854.
- Kollmann F, Cote WA. 1968. Principles of wood science and technology I - Solid wood. Springer Verlag.
- Kord B, Kialashaki A, Kord B. 2010. The within-tree variation in wood density and shrinkage, and their relationship in *Populus euramericana*. *Turkish Journal of Agriculture and Forestry* 34: 121 - 126.
- Kozlowski TT, Kramer PJ, Pallardy SG. 1991. *The Physiological Ecology of Woody Plants*. Academic Press, San Diego.
- Kraus JE, Arduin M. 1997. Manual básico de métodos em morfologia vegetal. Seropédica, Rio de Janeiro.
- Lachenbruch B, McCulloh KA. 2014. Traits, properties, and performance: how woody plants combine hydraulic and mechanical functions in a cell, tissue, or whole plant. *New Phytologist* 204: 747 - 764.
- Lamy J, Delzon S, Bouche PS, Alia R, Vendramin GG, Cochard H, et al. 2014. Limited genetic variability and phenotypic plasticity detected for cavitation resistance in a Mediterranean pine. *New Phytologist* 201: 874 - 886.
- Larter M, Brodribb TJ, Pfautsch S, Burlett R, Cochard H, Delzon S. 2015. Extreme aridity pushes trees to their physical limits. *Plant Physiology* 168: 804 - 807.
- Larter M, Pfautsch S, Domec J-C, Trueba S, Nagalingum N, Delzon S. 2017. Aridity drove the evolution of extreme embolism resistance and the radiation of conifer genus *Callitris*. *New Phytologist* 215: 97 - 112.
- Lazzarin M, Crivellaro A, Williams CB, Dawson TE, Mozzi G, Anfodillo T. 2016. Tracheid and pit anatomy vary in tandem in a tall *Sequoiadendron giganteum* tree. *IAWA Journal* 37: 172 - 185.
- Lefcheck JS. 2015. piecewiseSEM: Piecewise structural equation modelling in R for ecology, evolution, and systematics. *Methods in Ecology and Evolution* 7: 573 - 579.
- Lens F, Luteyn JL, Smets E, Jansen S. 2004. Ecological trends in the wood anatomy of Vaccinioideae (Ericaceae s.l.). *Flora* 199: 309 - 319.
- Lens F, Sperry JS, Christman MA, Choat B, Rabaey D, Jansen S. 2011. Testing hypotheses that link wood anatomy to cavitation resistance and hydraulic conductivity in the genus *Acer*. *New Phytologist* 190: 709 - 723.
- Lens F, Eeckhout S, Zwartjes R, Smets E, Janssens S. 2012a. The multiple fuzzy origins of woodiness within Balsaminaceae using an integrated approach. Where do we draw the line? *Annals of Botany* 109: 783 - 799.
- Lens F, Smets E, Melzer S. 2012b. Stem anatomy supports *Arabidopsis thaliana* as a model for insular woodiness. *New Phytologist* 193: 12 - 17.
- Lens F, Tixier A, Cochard H, Sperry JS, Jansen S, Herbette S. 2013a. Embolism resistance as a key mechanism to understand adaptive plant strategies. *Current Opinion in Plant Biology* 16: 287 - 292.
- Lens F, Davin N, Smets E, del Arco M. 2013b. Insular woodiness on the Canary Islands: remarkable case of convergent evolution. *International Journal of Plant Sciences* 174: 992 - 1013.

Lens F, Picon-Cochard C, Delmas CEL, Signarbieux C, Buttler A, Cochard H, *et al.* 2016. Herbaceous angiosperms are not more vulnerable to drought-induced embolism than angiosperm trees. *Plant Physiology* 172: 661 - 667.

Li S, Lens F, Espino S, Karimi Z, Klepsch M, Schenk HJ, *et al.* 2016. Intervessel pit membrane thickness as a key determinant of embolism resistance in angiosperm xylem. *IAWA Journal* 37: 152 - 171.

Ligrone R, Duckett JG, Renzaglia KS. 2012. Major transitions in the evolution of early land plants: a bryological perspective. *Annals of Botany* 109: 851 - 871.

Loepfe L, Martínez-Vilalta J, Pinol J, Mencuccini M. 2007. The relevance of xylem network structure for plant hydraulic efficiency and safety. *Journal of Theoretical Biology* 247: 788 - 803.

Lucas JW, Groover A, Lichtenberger R, Furuta K, Yadav S, Helariutta Y, *et al.* 2013. The plant vascular system: evolution, development and functions. *Journal of Integrative Plant Biology* 55: 294 - 388.

Lupi C, Morin H, Deslauriers A, Rossi S, Houle D. 2012. Increasing nitrogen availability and soil temperature: effects on xylem phenology and anatomy of mature black spruce. *Canadian Journal of Forest Research* 42: 1277 - 1288.

Maherali H, Pockman WT, Jackson RB. 2004. Adaptive variation in the vulnerability of woody plants to xylem cavitation. *Ecology* 85: 2184 - 2199.

Maherali H, Walden AE, Husband BC. 2009. Genome duplication and the evolution of physiological responses to water stress. *New Phytologist* 184: 721 - 731.

Marcati CR, Angyalossy-Alfonso V, Benetati L. 2001. Anatomia comparada do lenho de *Copaifera langsdorffii* Desf. (Leguminosae-Caesalpinoideae) de floresta e cerradão. *Revista Brasileira de Botânica* 24: 311 - 320.

Martin-St Paul N, Longepierre D, Huc R, Delzon S, Burlett R, Joffre R, *et al.* 2014. How reliable are methods to assess xylem vulnerability to cavitation? The issue of 'open vessel' artifact in oaks. *Tree Physiology* 34: 894 - 905.

Martinez-Cabrera HI, Jones CS, Espino S, Schenk HJ. 2009. Wood anatomy and wood density in shrubs: responses to varying aridity along transcontinental transects. *American Journal of Botany* 96: 1388 - 1398.

Martinez-Vilalta J, Cochard H, Mencuccini M, Sterck F, Herrero A, Korhonen JFJ, *et al.* 2009. Hydraulic adjustment of Scots pine across Europe. *New Phytologist* 184: 353 - 364.

Martinez-Vilalta J, Muncuccini M, Vayreda J, Retana J. 2010. Interspecific variation in functional traits, not climatic differences among species ranges, determines demographic rates across 44 temperate and Mediterranean tree species. *Journal of Ecology* 98: 1462 - 1475.

Mattheck C, Kubler H. 1995. Wood – the internal optimization of trees. Springer-Verlag, Berlin.

Mattos BD, Gatto DA, Stangerlin DM, Calegari L, Melo RR, Santini EJ. 2011. Variação axial da densidade básica da madeira de três espécies de gimnospermas. *Brazilian Journal of Agricultural Sciences* 6: 121 -126.

McCulloh KA, Sperry JS. 2005. Patterns in hydraulic architecture and their implications for transport efficiency. *Tree Physiology* 25: 257 - 267.

McDowell NG, Phillips N, Lunch C, Bond BJ, Ryan MG. 2002. An investigation of hydraulic limitation and compensation in large, old Douglas-fir trees. *Tree Physiology* 22: 763 - 774.

McDowell NG, Pockman WT, Allen CD, Breshears DD, Cobb N, Kolb T, *et al.* 2008. Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? *New Phytologist* 178: 719 - 739.

- Meinzer FC, Woodruff DR, Domec J-C, Goldstein G, Campanello PI, Gatti MG, et al. 2008. Coordination of leaf and stem water transport properties in tropical forest trees. *Oecologia* 156: 31 - 41.
- Meinzer FC, McCulloh KA, Lachenbruch B, Woodruff DR, Johnson DM. 2010. The blind men and the elephant: the impact of context and scale in evaluating conflicts between plant hydraulic safety and efficiency. *Oecologia* 164: 287 - 296.
- Mencuccini M, Comstock J. 1999. Variability in hydraulic architecture and gas exchange of common bean (*Phaseolus vulgaris*) cultivars under well-watered conditions: interactions with leaf size. *Australian Journal of Plant Physiology* 26: 115 - 124.
- Mendiburu F. 2017. *Agricolae: Statistical Procedures for Agricultural Research*. R package version 1.2-8. <https://CRAN.R-project.org/package=agricolae>.
- Metcalfe CR, Chalk L. 1950. Anatomy of the Dicotyledons. Vol. 1, Clarendon Press, Oxford.
- Metcalfe CR. 1973. Metcalfe and Chalk's anatomy of the dicotyledons and its revision. *Taxon* 22: 659 - 668.
- Metzner R, Thorpe MR, Breuer U, Blumler P, Schurr U, Schneider H, et al. 2010. Contrasting dynamics of water and mineral nutrients in stems shown by stable isotope tracers and cryo-SIMS. *Plant, Cell & Environment* 33: 1393 - 1407.
- Meyra AG, Kuz VA, Zarragoicochea GJ. 2007. Geometrical and physicochemical considerations of the pit membrane in relation to air seeding: the pit membrane as a capillary valve. *Tree Physiology* 27: 1401 - 1405.
- Mrad A, Domec J-C, Huang C-W, Lens F, Katul G. 2018. A network model links wood anatomy to xylem tissue hydraulic behaviour and vulnerability to cavitation. *Plant, Cell & Environment* 41: 2718 - 2730.
- Monfreda C, Ramankutty N, Foley JA. 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles* 22: Gb1022.
- Morretes BL, Ferri MG. 1959. Contribuição ao estudo da anatomia das folhas de plantas do cerrado. *Boletim da Faculdade de Filosofia Ciências e Letras* 243: 7–70.
- Morris H, Plavcová L, Gorai M, Klepsch MM, Kotowska M, Schenk HJ, et al. 2018. Vessel-associated cells in angiosperm xylem: highly specialized living cells at the symplast–apoplast boundary. *American Journal of Botany* 105: 151 - 160.
- Moro MF, Lughada EN, Filer DL, Araújo FS, Martins FR. 2014. A catalogue of the vascular plants of the Caatinga Phytogeographical Domain: a synthesis of floristic and phytosociological surveys. *Phytotaxa* 160: 1 - 118.
- Moro MF, Lughadha EN, Araújo FS, Martins FR. 2016. A phytogeographical meta-analysis of the semiarid Caatinga domain in Brazil. *Botanical Review* 82: 91 - 148.
- Moya R, Perez LD, Arce V. 2003. Wood density of *Tectona grandis* at two plantation spacings in Costa Rica. *Journal of Tropical Forest Products* 9: 153 - 161.
- Nakagawa S, Schielzeth H. 2013. A general and simple method for obtaining R^2 from generalized linear mixed-effect models. *Methods in Ecology and Evolution* 4: 133 - 142.
- Nardini A, Lo Gullo MA, Salleo S. 2011. Refilling embolized xylem conduits: is it a matter of phloem unloading? *Plant Sciences* 180: 604 - 611.

Nolf M, Pagitz K, Mayr S. 2014. Physiological acclimation to drought stress in *Solidago canadensis*. *Physiologia Plantarum* 150: 529 - 539.

Nolf M, Rosani A, Ganthaler A, Beikircher B, Mayr, S. 2016. Hydraulic variation in three *Ranunculus* species. *Plant Physiology* 170: 2085 - 2094.

Nimer E. 1972. Climatologia da Região Nordeste do Brasil. *Revista Brasileira de Geografia* 34: 3 - 51.

O'Brien MJ, Leuzinger S, Philipson CD, Tay J, Hector A. 2014. Drought survival of tropical tree seedlings enhanced by non-structural carbohydrate levels. *Nature climate change* 4: 710 - 714.

O'Brien MJ, Engelbrecht BMJ, Joswig J, Pereyra G, Schuldt B, Jansen S, et al. 2017. A synthesis of tree functional traits related to drought induced mortality in forests across climatic zones. *Journal of Applied Ecology* 54: 1669 - 1686.

Oberprieler C, Himmelreich S, Källersjö M, Vallès J, Watson LE, Vogt R. 2009. Anthemidae. In: Funk VA, Susanna A, Stuessy TF, Bayer RJ (Eds.), Systematics, evolution, and biogeography of Compositae. International Association for Plant Taxonomy, Vienna, pp: 631 - 666.

Ogasa M, Miki NH, Murakami Y, Yoshikawa K. 2013. Recovery performance in xylem hydraulic conductivity is correlated with cavitation resistance for temperate deciduous tree species. *Tree Physiology* 33: 335 - 344.

Oksanen J, Blanchet FG, Kindt R, Legendre P, Minchin PR, O'Hara RB, et al. 2015. Vegan: Community Ecology, Available online at: <http://CRAN.R-project.org/package=vegan>.

Oliveira PS, Marques RJ. 2002. The Cerrado of Brazil: Ecology and Natural History of a Neotropical Savanna. Columbia University Press, New York.

Oliveira AFM, Meirelles ST, Salatino A. 2003. Epicuticular waxes from caatinga and cerrado species and their efficiency against water loss. *Anais da Academia Brasileira de Ciências* 75: 431 - 439.

Oliveira RS, Bezerra L, Davidson EA, Pinto F, Klink CA, Nepstad DC, et al. 2005. Deep root function in soil water dynamics in cerrado savannas of central Brazil. *Functional Ecology* 19: 574 - 581.

Oliveira RS, Costa FRC, van Baalen E, Jonge A, Bittencourt PR, Almanza Y, et al. In press. Embolism resistance drives the distribution of Amazonian rainforest tree species along hydro-typographic gradients. *New Phytologist*. doi: 10.1111/nph.15463

Olson ME. 2012. Linear trends in botanical systematics and the major trends of xylem evolution. *Botanical Review* 78: 154 - 183.

Olson ME, Rosell J. 2013. Vessel diameter–stem diameter scaling across woody angiosperm and the ecological causes of xylem vessel diameter variation. *New Phytologist* 197: 1204 - 1213.

Olson ME, Rosell J, Léon C, Zamora S, Weeks A, Alvarado-Cárdenas LO, et al. 2013. Convergent vessel diameter–stem diameter scaling across five clades of new and old world eudicots from desert to rain forest. *International Journal of Plant Sciences* 174: 1062 - 1078.

Olson ME. 2014. Xylem hydraulic evolution, I.W. Bailey, and Nardini & Jansen (2013): Pattern and process. *New Phytologist* 203: 7 - 11.

Olson ME, Anfodillo T, Rosell J, Petit G, Crivellaro A, Isnard S, et al. 2014. Universal hydraulics of the flowering plants: vessel diameter scales with stem length across angiosperm lineages, habits and climates. *Ecology Letters* 17: 988 - 997.

Olson ME, Soriano D, Rosell JA, Anfodillo T, Donoghue MJ, Edwards EJ, et al. 2018. Plant height and hydraulic vulnerability to drought and cold. *Proceedings of the National Academy of Sciences USA* 115: 7551 - 7556.

- Onoda Y, Richards AE, Westoby M. 2010. The relationship between stem biomechanics and wood density is modified by rainfall in 32 Australian woody plant species. *New Phytologist* 185: 493 - 501.
- Pammerer NW, Van der Willigen C. 1998. A mathematical and statistical analysis of the curves illustrating vulnerability of xylem to cavitation. *Tree Physiology* 18: 589 - 593.
- Pennington, T.R., Prado, D.E., Pendry, C.A., 2000. Neotropical seasonally dry forests and Quaternary vegetation changes. *Journal of Biogeography* 27: 261 - 273.
- Pereira L, Bittencourt PRL, Oliveira RS, Junior MBM, Barros FV, Ribeiro RV, et al. 2016. Plant pneumatics: stem air flow is related to embolism – new perspectives on methods in plant hydraulics. *New Phytologist* 211: 357 - 370.
- Pereira L, Domingues-Junior AP, Jansen S, Choat B, Mazzafera P. 2017. Is embolism resistance in plant xylem associated with quantity and characteristics of lignin? *Trees* 32: 349 - 358.
- Petit G, Pfautsch S, Anfodillo T, Adams MA. 2010. The challenge of tree height in *Eucalyptus regnans*: when xylem tapering overcomes hydraulic resistance. *New Phytologist* 187: 1146 - 1153.
- Pfautsch S, Keitel C, Turnbull TL, Braimbridge MJ, Wright TE, Simpson RR, et al. 2011. Diurnal patterns of water use in *Eucalyptus viminalis* indicate pronounced desiccation-rehydration cycles despite unlimited water supply. *Tree Physiology* 31: 1041 - 1051.
- Pfautsch S, Renard J, Tjoelker MG, Salih A. 2015a. Phloem as capacitor: radial transfer of water into xylem of tree stems occurs via symplastic transport in ray parenchyma. *Plant Physiology* 167: 963 - 971.
- Pfautsch S, Holtta T, Mencuccini M. 2015b. Hydraulic functioning of tree stems: fusing ray anatomy, radial transfer and capacitance. *Tree Physiology* 35: 706 - 722.
- Pfautsch S, Aspinwall MJ, Drake JE, Chacon-Doria L, Langelaan RJA, Tissue DT, et al. 2018. Traits and trade-offs in whole-tree hydraulic architecture along the vertical axis of *Eucalyptus grandis*. *Annals of Botany* 121: 129 - 141.
- Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team. 2016. nlme: linear and nonlinear mixed effects models. R package version 3.1-126. <http://CRAN.R-project.org/package=nlme>.
- Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team. 2018. nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-137. <https://CRAN.R-project.org/package=nlme>.
- Pittermann J, Sperry JS. 2003. Tracheid diameter is the key trait determining the extent of freezing-induced embolism in conifers. *Tree Physiology* 23: 907 - 914.
- Pittermann J. 2010. The evolution of water transport in plants: an integrated approach. *Geobiology* 8: 112 - 139.
- Pittermann J, Choat B, Jansen S, Stuart SA, Lynn L, Dawson TE. 2010. The Relationships between xylem safety and hydraulic efficiency in the Cupressaceae: the evolution of pit membrane form and function. *Plant Physiology* 153: 1919 - 1931.
- Pivovarov AL, Pasquini SC, Guzman ME, Alstad KP, Stemke JS, Santiago LS. 2015. Multiple strategies for drought survival among woody plant species. *Functional Ecology* 30: 517 - 526.
- Plavcová L, Jansen S, Klepsch M, Hacke UG. 2013. Nobody's perfect: can irregularities in pit structure influence vulnerability to cavitation? *Frontiers in Plant Science* 4: 1 - 6.
- Plavcová L, Jansen S. 2015. The role of xylem parenchyma in the storage and utilization of non-structural carbohydrates. In: Hacke UW (Ed.), *Functional and ecological xylem anatomy*. Springer International Publishing, Switzerland, pp: 209 - 234.

Pockman WT, Sperry JS, O'Leary JW. 1995. Sustained and significant negative water pressure in xylem. *Nature* 378: 715 - 716.

Pockman WT, Sperry JS. 2000. Vulnerability to xylem cavitation and the distribution of Sonoran Desert vegetation. *American Journal of Botany* 87: 1287 - 1299.

Poorter L, Bongers L, Bongers F. 2006. Architecture of 54 moist forest tree species: traits, trade-offs, and functional groups. *Ecology* 87: 1289 - 1301.

Poorter L, McDonald I, Alarcón A, Fichtler E, Licona J-C, Peña-Claros M. 2010. The importance of wood traits and hydraulic conductance for the performance and life history strategies of 42 rainforest tree species. *New Phytologist* 185: 481 - 492.

Pratt RB, Jacobsen AL, Golgotiu KA, Sperry JS, Ewers FW, Davis SD. 2007. Life history type and water stress tolerance in nine California chaparral species (Rhamnaceae). *Ecology Monographs* 77: 239 - 253.

Pratt RB, Jacobsen AL. 2017. Conflicting demands on angiosperm xylem: tradeoffs among storage, transport and biomechanics. *Plant, Cell & Environment* 40: 897 - 913.

Preston KA, Cornwell WK, DeNoyer JL. 2006. Wood density and vessel traits as distinct correlates of ecological strategy in 51 California coast range angiosperms. *New Phytologist* 170: 807 - 818.

R Core Team, 2014. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria, URL <http://www.R-project.org/>.

R Core Team. 2016. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna. URL <http://www.R-project.org/>.

R Core Team. 2017. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna. <http://www.R-project.org>.

R Studio Team. 2016. RStudio: Integrated Development for R. RStudio, Inc., Boston. <http://www.rstudio.com/>

Raij B, van Andrade JC, Cantarella H, Quaggio JA. 2001. Análise química para avaliação da fertilidade do solo. Instituto Agronômico, Campinas.

Rahmstorf S, Coumou D. 2012. A decade of weather extremes. *Nature Climate Change* 2: 491 - 496.

Ratter JA, Bridgewater S, Ribeiro JF. 2003. Analysis of the floristic composition of the Brazilian cerrado vegetation III: comparison of the woody vegetation of 376 areas. *Edinburgh Journal of Botany* 60: 57 - 109.

Reiterer A, Burgert I, Sinn G, Tschech S. 2002. The radial reinforcement of the wood structure and its implication on mechanical and fracture mechanical properties -- a comparison between two tree species. *Journal of Materials Sciences* 37: 935 - 940.

Rivera G, Elliot S, Caldas LS, Nicolossi G, Coradin VTR, Borchert R. 2002. Increasing day length induces spring flushing in tropical dry forest trees in the absence of rain. *Trees* 16: 445 - 456.

Rosell JA, Olson ME, Anfodillo T. 2017. Scaling of xylem vessel diameter with plant size: causes, predictions, and outstanding questions. *Current Forestry Reports* 3: 46 - 59.

Rosenthal DM, Stiller V, Sperry JS, Donovan LA. 2010. Contrasting drought tolerance strategies in two desert annuals of hybrid origin. *Journal of experimental botany* 61: 2769 - 2778.

Rosner S. 2017. Wood density as a proxy for vulnerability to cavitation: size matters. *Journal of Plant Hydraulics* 4: 1 - 10.

Salatino A. 1993. Chemical ecology and the theory of oligotrophic scleromorphism. *Anais da Academia Brasileira de Ciências* 65: 1 - 13.

- Salleo S, Lo Gullo MA, Trifilo P, Nardini A. 2004. New evidence for a role of vessel-associated cells and phloem in the rapid xylem refilling of cavitated stems of *Laurus nobilis* L. Plant, Cell & Environment 27: 1065 - 1076.
- Salleo S, Trifilò P, Lo Gullo MA. 2006. Phloem as a possible major determinant of rapid cavitation reversal in stems of *Laurus nobilis* (laurel). Functional Plant Biology 33: 1063 - 1074.
- Salleo S, Trifiló P, Lo Gullo MA. 2008. Vessel wall vibrations: trigger for embolism repair. Functional Plant Biology 35: 289 - 297.
- Salleo S, Trifiló P, Esposito S, Nardini A, Lo Gullo MA. 2009. Starch-to-sugar conversion in wood parenchyma of field-growing *Laurus nobilis* plants: a component of the signal pathway for embolism repair? Functional Plant Biology 36: 815 - 825.
- Sass JE. 1951. Botanical Microtechnique, 20 ed. The Iowa State College Press, Ames.
- Scholz FG, Bucci SJ, Goldstein G, Meinzer FC, Franco AC, Miralles-Wilhelm F. 2007. Biophysical properties and functional significance of stem water storage tissues in Neotropical savannah trees. Plant, Cell & Environment 30: 236 - 248.
- Scholz A, Klepsch M, Karimi Z, Jansen S. 2013. How to quantify conduits in wood? Frontiers in Plant Sciences 56: 1 - 11.
- Scholz FG, Phillips NG, Bucci SJ, Meinzer FC, Goldstein G. 2011. Hydraulic capacitance: biophysics and functional significance of internal water sources on relation to tree size. In: Meinzer FC, Phillips NG, Bucci SJ, Meinzer FC, Goldstein G (Eds.), Size-and age-related changes in tree structure. Springer Science Business Media, pp: 341 - 361.
- Schenk HJ, Steppe K, Jansen S. 2015. Nanobubbles: a new paradigm for air-seeding in xylem. Trends in Plant Science 20: 199-205.
- Schenk HJ, Espino S, Romo DM, Nima N, Do AYT, Michaud JM, et al. 2017. Xylem surfactants introduce a new element to the cohesion-tension theory. Plant Physiology 173: 1177 - 1196.
- Schenk HJ, Espino S, Rich-Cavazos SM, Jansen S. 2018. From the sap's perspective: the nature of vessel surfaces in angiosperm xylem. American Journal of Botany 105: 172 - 185.
- Schindelin J, Carreras A, Frise E, Kaynig V, Longair M, Pietzsch T, et al. 2012. Fiji - an Open Source platform for biological image analysis. Nature Methods 9: 676 - 682.
- Schreiber S, Hacke UG, Hamann A. 2015. Variation of xylem vessel diameters across a climate gradient: insight from a reciprocal transplant experiment with a widespread boreal tree. Functional Ecology 29: 1392 - 1401.
- Schweingruber FH. 2007. Wood structure and environment. Springer-Verlag, Berlin.
- Schweingruber FH, Borner A, Schulze ED. 2011. Atlas of stem anatomy in herbs, shrubs and trees. Vol. 1. Springer, Heidelberg.
- Shoemaker HE, McLean EO, Pratt PF. 1961. Buffer methods for determining the lime requirement of soils with appreciable amounts of extractable aluminum. Soil Science Society of America Proceedings 25: 274 -277.
- Silva FAM, Assad ED, Evangelista BA. 2008. Caracterização climática do bioma cerrado. In: Sano, S.M., Almeida, S.P., Ribeiro, J.F. (Eds.), Cerrado: Ecologia e Flora. Embrapa, Brasília, pp: 71 - 88.
- Skelton RP, Brodribb TJ, Choat B. 2017. Casting light on xylem vulnerability in an herbaceous species reveals a lack of segmentation. New Phytologist 214: 561 - 569.
- Solereder H. 1908. Systematic anatomy of the Dicotyledons: a handbook for laboratories of pure and applied botany. Vol. 2, Clarendon Press, Scott, Oxford.

Sonsin JO, Gasson GE, Barros CF, Marcato CR. 2012. A comparison of the wood anatomy of 11 species from two cerrado habitats (cerado s.s and adjacent gallery forest). *Botanical Journal of the Linnean Society* 170: 257 - 276.

Soudzilovskaia NA, Elumeeva TG, Onipchenko VG, Shidakov II, Salpagarova FS, Khubiev AB, et al. 2013. Functional traits predict relationship between plant abundance dynamic and long-term climate warming. *Proceedings of the National Academy of Science USA* 110: 18180 - 18184.

Souza MC, Franco AC, Haridasan M, Rossatto DR, Araújo JF, Morellato LPC, et al. 2015. The length of the dry season may be associated with leaf scleromorphism in cerrado plants. *Anais da Academia Brasileira de Ciências* 87: 1691 - 1699.

Sperry JS, Donnelly JR, Tyree MT. 1988. Seasonal occurrence of xylem embolism in sugar maple (*Acer saccharum*). *American Journal of Botany* 75: 1212 - 1218.

Sperry JS, Tyree MT. 1988. Mechanism of water stress-induced xylem embolism. *Plant Physiology* 88: 581 - 587.

Sperry J, Sullivan EM. 1992. Xylem embolism in response to freeze-thaw cycles and water stress in ring-porous, diffuse-porous, and conifer species. *Plant Physiology* 100: 605 - 613.

Sperry JS, Nichols KL, Sullivan JEM. 1994. Xylem embolism in ring-porous, diffuse-porous, and coniferous trees of Northern Utah and Interior Alaska. *Ecology* 75: 1736 – 1752.

Sperry J, Hacke U. 2002. Desert shrub water relations with respect to soil characteristics and plant functional type. *Functional Ecology* 16: 367 - 378.

Sperry JS. 2003. Evolution of water transport and xylem structure. *International Journal of Plant Sciences* 164: 115 - 127.

Sperry JS, Hacke UG, Wheeler JK. 2005. Comparative analysis of end wall resistivity in xylem conduits. *Plant, Cell & Environment* 28: 456 - 465.

Sperry JS, Hacke UG, Pittermann J. 2006. Size and function in conifer tracheids and angiosperm vessels. *American Journal of Botany* 93: 1490 - 1500.

Sperry JS, Meinzer FC, McCulloh KA. 2008. Safety and efficiency conflicts in hydraulic architecture: scaling from tissues to trees. *Plant, Cell & Environment* 31: 632 - 645.

Spicer R. 2014. Symplasmic networks in secondary vascular tissues: parenchyma distribution and activity supporting long-distance transport. *Journal of Experimental Botany* 65: 1829 - 1848.

Spicer R. 2016. Variation in angiosperm wood structure and its physiological and evolutionary significance. In: Groover A, Cronk Q (eds.), *Comparative and Evolutionary Genomics of Angiosperm Trees*. Springer, Switzerland, pp:19 - 60.

Stiller V, Sperry JS. 2002. Cavitation fatigue and its reversal in sunflower (*Helianthus annuus* L.). *Journal of Experimental Botany* 53: 1155 - 1161.

Thornthwaite CW. 1948. An approach toward a rational classification of climate. *Geographical Review* 38: 55 - 94.

Tixer A, Cochard H, Badel E, Dusotoit-Coucaud A, Jansen S, Herbette S. 2013. *Arabidopsis thaliana* as a model species for xylem hydraulics: does size matter? *Journal of Experimental Botany* 64: 2295 - 2305.

Tng DYP, Apgaua DMG, Ishida YF, Mencuccini M, Lloyd J, Laurance WF, et al. In press. Rainforest trees respond to drought by modifying their hydraulic architecture. *Ecology and Evolution* 1 - 13.

- Torres-Ruiz JM, Cochard H, Mayr S, Beikircher B, Diaz-Espejo A, Rodriguez-Dominguez CM, et al. 2014. Vulnerability to cavitation in *Olea europaea* current-year shoots: further evidence of an open-vessel artifact with centrifuge and air-injection techniques. *Physiologia Plantarum* 152: 465 - 474.
- Torres-Ruiz JM, Jansen S, Choat B, McElrone AJ, Cochard H, Brodribb TJ, et al. 2015. Direct micro-CT observation confirms the induction of embolism upon xylem cutting under tension. *Plant Physiology* 167: 40 - 43.
- Trifiló P, Barbera PM, Raimondo F, Nardini A, Lo Gullo MA. 2014. Coping with drought-induced xylem cavitation: coordination of embolism repair and ionic effects in three Mediterranean evergreens. *Tree Physiology* 34: 109 - 122.
- Trueba S, Pouteau R, Lens F, Field TS, Isnard S, Olson ME, et al. 2017. Vulnerability to xylem embolism as a major correlate of the environmental distribution of rainforest species on a tropical island. *Plant, Cell & Environment* 40: 277 - 289.
- Tyree MT, Sperry JS. 1989. Vulnerability of xylem to cavitation and embolism. *Annual Review of Plant Physiology and Plant Molecular Biology* 40: 19 - 38.
- Tyree MT, Alexander J, Machado JL. 1992. Loss of hydraulic conductivity due to water stress in intact juveniles of *Quercus rubra* and *Populus deltoides*. *Tree Physiology* 10: 411 - 415.
- Tyree MT, Davis SD, Cochard H. 1994. Biophysical perspectives of xylem evolution – is there a tradeoff of hydraulic efficiency for vulnerability to dysfunction. *IAWA Journal* 15: 335 - 360.
- Tyree MT, Zimmermann MH. 2002. *Xylem Structure and the Ascent of Sap*. Springer, Berlin.
- Tyree MT. 2003. Hydraulics limits on tree performance: transpiration, carbon gain and growth of trees. *Trees – Structure and Function* 17: 95 - 100.
- UNEP. 1997. *World Atlas of Desertification*. United nations Environmental Program. Nairobi, Kenya.
- Urli M, Porté AJ, Cochard H, Guengant Y, Burlett R, Delzon S. 2013. Xylem embolism threshold for catastrophic hydraulic failure in angiosperm trees. *Tree Physiology* 33: 672 - 683.
- Van Bell AJE. 1990. Xylem-phloem exchange via the rays: the undervalued route of transport. *Journal of Experimental Botany* 41: 631 - 644.
- Van den Oever L, Baas P, Zandee M. 1981. Comparative wood anatomy of *Symplocos* and latitude and altitude of provenance. *IAWA Bulletin* 2: 3 - 24.
- Venturas MD, Sperry JS, Hacke UG. 2017. Plant xylem hydraulics: what we understand, current research, and future challenges. *Journal of Integrative Plant Biology* 59: 356 - 389.
- Volaire F, Lens F, Cochard H, Xu H, Chacon-Dória L, Bristiel P, et al. 2018. Embolism and mechanical resistances play a key role in dehydration tolerance of a perennial grass *Dactylis glomerata* L. *Annals of Botany* 22: 325 - 336.
- Wallace AR. 1878. *Tropical nature and other essays*. Macmillan Press, London.
- Walkley A, Black IA. 1934. An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science (Baltimore)* 37: 29 - 38.
- Walter H. 1973. *Vegetation of the Earth*. Springer, New York.
- Wang R, Zhang L, Zhang S, Cai J, Tyree MT. 2014. Water relations of *Robinia pseudoacacia* L.: Do vessels cavitate and refill diurnally or are R-shaped curves invalid in Robinia? *Plant, Cell & Environment* 37: 2667 - 2678.

West GB, Brown JH, Enquist BJ. 1999. A general model for the structure and allometry of plant vascular systems. *Nature* 400: 664.

Wheeler JK, Sperry JS, Hacke UG, Hoang N. 2005. Intervessel pitting and cavitation in woody Rosaceae and other vessel vesselled plants: a basis for a safety versus efficiency trade-off in xylem transport. *Plant, Cell & Environment* 28: 800 - 812.

Whittaker RJ, Fernandez-Palacios JM. 2007. Island biogeography: ecology, evolution, and conservation, 2nd ed. Oxford University Press, Oxford.

Williamson GB, Wiemann MC. 2010. Measuring wood specific gravity...correctly. *American Journal of Botany* 97: 519 - 524.

Woodruff DR, Meinzer FC, McCulloh KA. 2016. Forest canopy hydraulics. In: Hikosaka K, Niinemets U, Anten NPR (Eds.), *Canopy Photosynthesis: from Basics to Applications*. Springer Dordrecht, New York London, pp: 187 - 218.

Woodrum CL, Ewers FW, Telewski FW. 2003. Hydraulic, biomechanical, and anatomical interactions of xylem from five species of *Acer* (Aceraceae). *American Journal of Botany* 90: 693 - 699.

Wortemann R, Herbette S, Barigah TS, et al. 2011. Genotypic variability and phenotypic plasticity of cavitation resistance in *Fagus sylvatica* L. across Europe. *Tree Physiology* 31: 1175 - 1182.

Zanne AE, Westoby M, Falster DS, Ackerly DD, Loarie SR, Arnold SEJ, et al. 2010. Angiosperm wood structure: global patterns in vessel anatomy and their relation to wood density and potential conductivity. *American Journal of Botany* 97: 207 - 215.

Zhang YJ, Rockwell FE, Graham AC, Alexander T, Holbrook M. 2016. Reversible leaf collapse: a potential "circuit breaker" against cavitation. *Plant Physiology* 172: 2261 - 2274.

Zhang Y, Lamarque LJ, Torres-Ruiz JM, Schuldt B, Karimi Z, Li S, et al. 2018. Testing the plant pneumatic method to estimate xylem embolism resistance in stems of temperate trees. *Tree Physiology* 38: 1016 - 1025.

Zheng J, Martínez-Cabrera HI. 2013. Wood anatomical correlates with theoretical conductivity and wood density across China: evolutionary evidence of the functional differentiation of axial and radial parenchyma. *Annals of Botany* 112: 927 - 935.

Zieminska K, Butler DW, Gleason SM, Wright IJ, Westoby M. 2013. Fibre wall and lumen fractions drive wood density variation across 24 Australian angiosperms. *Annals of Botany* 5: 1 - 14.

Zieminska K, Westoby M, Wright IJ. 2015. Broad anatomical variation within a narrow wood density range – A study of twig wood across 69 Australian angiosperms. *PLoS One* 10: 1 - 25.

Zimmermann MH, Brown CL. 1977. *Trees: structure and function*. Springer Verlag, New York.

Zimmermann MH. 1983. *Xylem Structure and the Ascent of Sap*. Springer, Berlin, Heidelberg, New York.

Zobel BJ, Sprague JR. 1998. *Juvenile wood in forest trees*. Springer, New York.

Zuur AF, Ieno EN, Walker N, Saveliev AA, Smith GM. 2009. Mixed effects models and extensions in ecology with R. Springer, New York.

Zuur AF, Ieno EN, Elphick CS. 2010. A protocol for data exploration to avoid common statistical problems. *Methods in Ecology and Evolution* 1: 3 – 14.

Zwieniecki MA, Secci F. 2015. Threats to xylem hydraulic function of trees under 'new climate normal' conditions. *New Phytologist* 38: 1713 - 1724.