Effect of natural and experimental droughts on the forest biogeochemical cycles

Case study of a highly instrumented beech forest of North-Eastern France

Touche J.[1,2], Calvaruso C. [3], De Donato P.[2], Turpault M-P.[1]
[1] INRAE, BEF, F-54000 Nancy, France
[2] UMR 7359, GeoRessources, Faculté des Sciences-Campus des Aiguillettes, 54506, Vandoeuvre-les-Nancy, France
[3] EcoSustain, Environmental Engineering Office, Research and Development, Kanfen, 57330, France

Climate changes induce an increase in frequency and intensity of phenomena exerting pressure on ecosystems (Easterling *et al.*, 2000; IPCC, 2021). Thus, in Europe, as well as in lots of other parts of the globe, more intense and repeated drought events are expected in the coming decades (Easterling *et al.*, 2000; Sánchez *et al.*, 2004; Cook, Ault and Smerdon, 2015; IPCC, 2021). In recent years, Europe already recorded important drought events during spring and summer (Ciais *et al.*, 2005; Hänsel *et al.*, 2019; Scharnweber *et al.*, 2020). Considering the many services provided by forests for economy, biodiversity, mitigation of greenhouse gas emission through carbon storage or even soil stability, it is of high importance to understand the impacts of drought on these ecosystems.

Currently, thanks to the numerous studies already carried out, drought effects are relatively well understood for various processes such as tree growth, mortality causes or carbon storage (Orwig and Abrams, 1997; Bréda *et al.*, 2006; McDowell *et al.*, 2008; Piao *et al.*, 2019). However, biogeochemical cycles and particularly nutrient circulation in drought conditions still suffer from a lack of knowledge (Kreuzwieser and Gessler, 2010; Schlesinger *et al.*, 2016; Gessler, Schaub and McDowell, 2017). Forest ecosystems in Europe are generally developed on nutrient-poor and unfertilized soil (Badeau, Dambrine and Walter, 1999), involving that tree nutrition is mainly ensured by recycling strategies such as organic matter mineralization within soil or nutrient internal recycling within trees. Moreover, it is known that an efficient nutrient circulation and a sufficient nutrient input are essential to the health of forest ecosystems, and are also water dependant (Marschner, 1995; Cakmak, 2005; Wieder *et al.*, 2015). Therefore, nutrient cycling can be expected to be negatively impacted during drought conditions through nutrient deficiencies which could contribute to forest dieback. The objectives of this work were to determine the effects of drought on the nutrient biogeochemical cycles, the specific mechanisms impacted and the consequences on tree nutrition.

To answer these objectives, in situ monitoring of biogeochemical cycles was carried out on the experimental site of Montiers-sur-Saulx, (Meuse, France). This site, implemented in 2012, is part of the AnaEE France research network and corresponds to a 143 ha forest developed on a soil sequence from deep acidic soil (Dystric Cambisol) to more or less shallow calcic soils (Eutric Cambisol and Rendzic Leptosol). The dominant species is the European beech (*Fagus sylvatica*), one of the most abundant deciduous trees in European temperate forests. Moreover, considering its drought sensitivity, beech sustainability could be threatened under future climate conditions(Leuschner, 2020; Scharnweber *et al.*, 2020). The soil is an Eutric Cambisol, representative of the region. On this site, the impact of various degrees of drought (Low – L, Medium – M and High – H) on the biogeochemical cycles was studied. Nutrient stocks and fluxes were calculated thanks to highly instrumented experiments allowing the monitoring of tree biomass, water volumes and nutrient concentrations in various compartments of the ecosystem (i.e., perennial biomass, green leaves, litterfall, soil, fine roots, atmospheric deposition, throughfall, stemflow and soil solution). In addition to field measurements, the water cycle was modelized daily thanks to a water model considering stand and soil characteristics. The L degree was assessed through the observation of natural droughts (2015, 2018 and 2019) on three plots of 2 500 m^2 each and operating since 2012 (Touche *et al.*, 2024). The M and H degrees were respectively assessed thanks to two rainfall exclusion experiments called REE_H (Touche *et al.*, 2022) and REE_M , operating since 2015 and 2020, respectively. Thus, for the REE_M and REE_H, a roof underneath canopy allowed exclusion of about 100% of the rainfall for a specific duration during the growing season. The rainfall exclusion duration was of 2.5 months and over 3 consecutive years for the REE_M and of 3.5 months and over 5 consecutive years for the REE_H. The plots subjected to these artificial droughts were compared to control plots subjected to unmodified natural precipitation regime.

The effects directly linked to the water deficit, measured in solution fluxes after 3 years of drought (M) are limited. The nutrient fluxes in soil solutions decrease, or even stop, during periods of drought, without necessarily modifying the total annual nutrient fluxes, thanks to a compensatory effect of the post-drought precipitations. Indeed, the release of nutrients by the holorganic layer is stimulated by of the post-drought precipitations. This work shows that the disruption of biogeochemical cycles by droughts is mainly indirectly induced by the evolution of the biomass production. The annual increment of the perennial aboveground biomass decreases, i.e., between -35% and -65% for M and H degrees, respectively. Leaf production decreases for M degree (-26%) leading to a drop in the leaf area index. Conversely, the production of fine roots greatly increases, i.e., between 35% and 115% for M and H degrees respectively. These responses could partly correspond to an adaptation of the stand to mitigate the water stress and ensure its resilience. However, these changes in biomass are achieved without a reduction in nutrient uptake, thus suggesting constant nutrient needs while a decrease in leaf biomass production induces lower resorption fluxes. In addition, the resorption efficiency of potassium (K) sharply decreases with the degree of drought, from 44% in the absence of drought event, to 31% for the L degree and 17% for the M degree. The H degree also induces a K deficiency in the production of green leaves. A decrease of K in the humus layer and in the superficial soil is also measured in the H degree as well as a mortality rate of 33% of the trees. Potassium deficiency may then be the direct consequence of maintaining the K need for biomass production associated with insufficient resorption efficiency and low-K availability in the soil. The high mortality rate at the end of the H degree experiment could therefore be the consequence of a double water and nutrient stress induced by 5 years of successive droughts.

This work, pioneer in the study of the consequences of droughts on nutrient cycles and tree nutrition, provides preliminary elements of responses. These conclusions must be confirmed and enriched by continuing the rain exclusion experiments on the Montiers site, but also on a larger scale, by taking into account the diversity of forest ecosystems (i.e. soil types and tree species) in France and Europe.

References

Badeau, V., Dambrine, E. and Walter, C. (1999) 'Propriétés des sols forestiers français : Résultats du premier inventaire systématique', pp. 165–180.

Bréda, N. *et al.* (2006) 'Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences', *Annals of Forest Science*, 63(6), pp. 625–644. Available at: https://doi.org/10.1051/forest:2006042.

Cakmak, I. (2005) 'The role of potassium in alleviating detrimental effects of abiotic stresses in plants', *Journal of Plant Nutrition and Soil Science*, 168(4), pp. 521–530. Available at: https://doi.org/10.1002/jpln.200420485.

Ciais, Ph. *et al.* (2005) 'Europe-wide reduction in primary productivity caused by the heat and drought in 2003', *Nature*, 437(7058), pp. 529–533. Available at: https://doi.org/10.1038/nature03972.

Cook, B.I., Ault, T.R. and Smerdon, J.E. (2015) 'Unprecedented 21st century drought risk in the American Southwest and Central Plains', *Science Advances*, 1(1), p. e1400082. Available at: https://doi.org/10.1126/sciadv.1400082.

Easterling, D.R. *et al.* (2000) 'Climate Extremes: Observations, Modeling, and Impacts', *Science*, 289(5487), pp. 2068–2074. Available at: https://doi.org/10.1126/science.289.5487.2068.

Gessler, A., Schaub, M. and McDowell, N.G. (2017) 'The Role of Nutrients in Drought-Induced Tree Mortality and Recovery', *New Phytologist*, 214(2), pp. 513–520. Available at: https://doi.org/10.1111/nph.14340.

Hänsel, S. *et al.* (2019) 'Assessing seasonal drought variations and trends over Central Europe', *Advances in Water Resources*, 127, pp. 53–75. Available at: https://doi.org/10.1016/j.advwatres.2019.03.005.

IPCC (ed.) (2021) 'Summary for Policymakers', in *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, pp. 3–32. Available at: https://doi.org/10.1017/9781009157896.001.

Kreuzwieser, J. and Gessler, A. (2010) 'Global climate change and tree nutrition: influence of water availability', *Tree Physiology*, 30(9), pp. 1221–1234. Available at: https://doi.org/10.1093/treephys/tpq055.

Leuschner, C. (2020) 'Drought response of European beech (Fagus sylvatica L.)—A review', *Perspectives in Plant Ecology, Evolution and Systematics*, 47, p. 125576. Available at: https://doi.org/10.1016/j.ppees.2020.125576.

Marschner, H. (1995) *Mineral Nutrition of Higher Plants, Second Edition*. 2nd Edition. Amsterdam: Academic Press.

McDowell, N. *et al.* (2008) 'Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought?', *New Phytologist*, 178(4), pp. 719–739. Available at: https://doi.org/10.1111/j.1469-8137.2008.02436.x.

Orwig, D.A. and Abrams, M.D. (1997) ‘Variation in radial growth responses to drought among species, site, and canopy strata’, *Trees-Structure and Function*, 11(8), pp. 474–484. Available at: https://doi.org/10.1007/s004680050110.

Piao, S. *et al.* (2019) ‘The impacts of climate extremes on the terrestrial carbon cycle: A review’, *Science China Earth Sciences*, 62(10), pp. 1551–1563. Available at: https://doi.org/10.1007/s11430-018-9363-5.

Sánchez, E. *et al.* (2004) ‘Future climate extreme events in the Mediterranean simulated by a regional climate model: a first approach’, *Global and Planetary Change*, 44(1), pp. 163–180. Available at: https://doi.org/10.1016/j.gloplacha.2004.06.010.

Scharnweber, T. *et al.* (2020) ‘Tree growth at the end of the 21st century-the extreme years 2018/19 as template for future growth conditions’, *Environmental Research Letters*, 15(7), p. 074022. Available at: https://doi.org/10.1088/1748-9326/ab865d.

Schlesinger, W.H. *et al.* (2016) ‘Forest biogeochemistry in response to drought’, *Global Change Biology*, 22(7), pp. 2318–2328. Available at: https://doi.org/10.1111/gcb.13105.

Touche, J. *et al.* (2022) ‘Five successive years of rainfall exclusion induce nutritional stress in a mature beech stand’, *Forest Ecology and Management*, 507, p. 119987. Available at: https://doi.org/10.1016/j.foreco.2021.119987.

Touche, J. *et al.* (2024) ‘Drought events influence nutrient canopy exchanges and green leaf partitioning during senescence in a deciduous forest’, *Forest Ecosystems*, p. 100173. Available at: https://doi.org/10.1016/j.fecs.2024.100173.

Wieder, W.R. *et al.* (2015) ‘Future productivity and carbon storage limited by terrestrial nutrient availability’, *Nature Geoscience*, 8(6), pp. 441–444. Available at: https://doi.org/10.1038/NGEO2413.