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Vulnerability to forest decline in a context of climate changes: new prospects about an old question in forest ecology

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1 Why focus on vulnerability?

Forest research has been particularly efficient in detecting the impacts of variability and long-term trends of climate. It is indeed in these ecosystems gathering perennial plants with a long lifespan that the first visible impacts of climate change have been convincingly documented. At first, positive changes in productivity were detected (Becker 1989; Becker et al. 1994; Badeau et al. 1995; Badeau et al. 1996). Improved growth conditions linked to warming, to nitrogen deposition and to increased atmospheric CO₂ were perceived fairly early and were also heterogeneous among biogeographical areas due to local limiting factors (trophic or climatic). The first thoughts about the Dryade project were initiated during 2006. In France, the first simulations of potential impacts of available climate scenarios generated awareness, criticism and concerns among managers and foresters (Carbofor, Loustau et al. 2005; Badeau et al. 2010). In addition to climate trends, extreme events had already been identified as a major cause of forest dieback. All major drought events were historically followed by cycles of dieback

(Innes et al. 1989; Jones et al. 1993; Landmann 1994; Beniston and Innes 1998; Thomas et al. 2002; Liang et al. 2003; Jurskis 2005). In France, forest dysfunctions induced by the drought events of 2003–2006 were mostly reversible (growth decrease, temporary degradation of crown conditions) but sometimes also irreversible (tree mortality). Several indicators of forest health surveys pointed to a degradation of forest health in France and Europe: abnormal increases in tree mortality (Pauly and Belrose 2005), decline of crown conditions (Lloret et al. 2004; Pauly and Belrose 2005; Belrose et al. 2004, 2006; Carnicer et al. 2011) and upsurge in biotic hazards (Nageleisen 2004; Piou et al. 2006; Rouault et al. 2006).

2 Need for common language

When the Dryade project started, the vulnerability concept was not yet fully appropriated by the research community in ecology. No measurement of the vulnerability of ecosystems to climate change was yet established. Generic concepts in ecology like the ecosystem resilience to disturbances (Holling 1986; Manion 1991, 2003; Jurskis 2005) and of concepts in geography and natural hazards (Briguglio 2004; Eriksen and Kelly 2007) have been debated. Several papers published concomitantly with the Dryade program (Bodin and Wiman 2007; Williams et al. 2008) allowed us to define the concepts underlying the research approach developed during Dryade. Vulnerability refers to the propensity or predisposition to be adversely affected by the effects of climate change, including climate variability and extreme weather events. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (IPCC 2014). In our perspective, the IPCC's definition was applied to forest ecosystems. Vulnerability is a relative notion (Fussler 2007) that should be fully qualified according to (1) the attribute of concern (in our forest context for example,

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Contribution of the co-authors Nathalie Bréda was the coordinator of the ANR-06-VULN-004 and has contributed as an editor associated with this special issue devoted to research conducted during the interdisciplinary research program “DRYADE”. She was particularly attentive to assist and support the publication of manuscripts of PhD students and young researchers supported by the project. Marianne Peiffer was involved in the management and coordination of the project; she also contributed as managing editor of *Annals of Forest Sciences* to publish this special issue.

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biodiversity, productivity, regeneration, mortality and decline) and (2) a temporal reference (past, current, future, dynamic i.e. immediate or delayed, multiannual or long term).

3 Research methods

Unlike what is sometimes claimed, the most vulnerable forest ecosystems are not necessarily mountain or Mediterranean forests, or forests with species at the margin of their distribution. The Dryade consortium investigated cases of forest dieback in the core of the production area in France for Douglas fir, beech or temperate oaks. Dryade mainly focussed on consequences of pulse disturbances like the 2003 heat and drought event and less on press disturbance like chronic acidification or temperature increase. Nevertheless, long-term trends were investigated with a retrospective approach using dendrochronological approaches. Parallel to Dryade (Bréda 2013), other projects focussed on modelling potential impacts on agro- and ecosystems using scenarios of future climate (CLIMATOR, ANR-06-VULN-014, QDIV, ANR-05-BDIV-009-01, GICC FAST) or ecosystem manipulation to simulate drought events (DROUGHT+, ANR-06-VULN-003). Brief summaries of these projects may be found in Granier (2013), Rambal (2013), Durand (2013) and Cheaib et al. (2012). Dryade concentrated on realized and direct impacts of acute drought stress, sometimes in interaction with insect or pest disturbances. Different approaches were mobilized to disentangle, identify and rank the determinants of vulnerability. The realized impacts from a natural hazard, of a given intensity, were quantified for several forest attributes of concern. Three types of attributes were investigated: tree health, radial growth and mortality (Dobbertin 2005). The realized impacts were quantified through (i) radial growth or productivity loss in reference to norms or to trees not exposed to the hazard or (ii) crown condition visually assessed as compared to a reference tree (dead branches, foliar loss and crown transparency). The database from the French Forest Health Department (<http://agriculture.gouv.fr/suivi-de-la-sante-des-forets>) was analysed to quantify and localize biotic hazards (pests and diseases) and their impact on forest decline. Growth response functions to climate and drought (quantified from soil water content derived from water balance models) were assessed for radial growth, tree ring texture or wood micro-density. Pairs of living and dead trees or healthy and declining trees were used to identify the traits describing individual vulnerability within stands and forests.

Identifying the determinants of the vulnerability of ecosystems implies to (1) identify the disturbance (climatic event, pest, disease or their interaction); (2) quantify its intensity/severity and (3) focus on the impacts of past hazards in the same forests. For instance, thanks to dendrochronology and retrospective water balance modelling, we quantified the

incidence of soil water deficits and other biotic events prior to the 2003 extreme event. Then, the extent to which past events interacted with the actual vulnerability of trees to extreme drought damage was taken into account (Beniston and Innes 1998). Indeed, we compared the response to recent hazard and to earlier drought events with similar intensity; we were able to demonstrate that the vulnerability to hazards increases with tree ageing.

4 Dryade's outputs and deliverables

To synthesize what was done, we adapted the core concepts described in the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX, IPCC 2012) to assess the risks of forest decline. The severity of adverse impacts of climate extremes (water deficit or excess) or biotic hazard depends on the severity of the extreme, on the exposure and on the vulnerability to the extreme (Fig. 1). We used here the SREX scheme to present the different papers collected in this special issue of *Annals of Forest Sciences*. Four components of vulnerability were investigated: (i) ecology–soil properties like extractable water, soil resistivity, topography and site fertility (Cailleret et al. 2014; Nourtier et al. 2014; Sergent et al. 2014b); (ii) tree ecophysiology–sap flux and its radial distribution as a function of changing water fluxes (Nourtier et al. 2014), carbon economy and radial distribution of carbohydrates in stems (Gérard and Bréda 2014); (iii) genetic diversity—among provenances (Sergent et al. 2014a) or species (Marçais and Desprez-Loustau 2014) and (iv) silviculture (Durand-Gillmann et al. 2014; Sergent et al. 2014b)—management, tree age and stand density. Main climatic events taken into account include periods of soil water deficit with their duration, intensity, date of occurrence and recurrence; this enabled us to assess the exposure of trees to water shortage taking into account local soil properties and stand properties (Nourtier et al. 2014; Sergent et al. 2014b). The risk components addressed in each paper from this special issue are indicated in Fig. 1.

Drought episodes during 2003–2006 were the driving factor of tree growth decrease, health decline and mortality for most of the species x regions studied cases. The repetition of drought episodes was more prejudicial than the absolute intensity and length of the 2003 extreme event itself. It induced a persistent growth decrease, a lack of recovery and even death of some individuals. Soil constraints to rooting, low water availability or low resistivity, delayed or inadequate thinning, tree age and sometimes nutrient availability were identified as the main vulnerability factors at stand level. At tree level, the vulnerability was related to species, provenance, and tree status and growth performance during juvenile growth or during years preceding

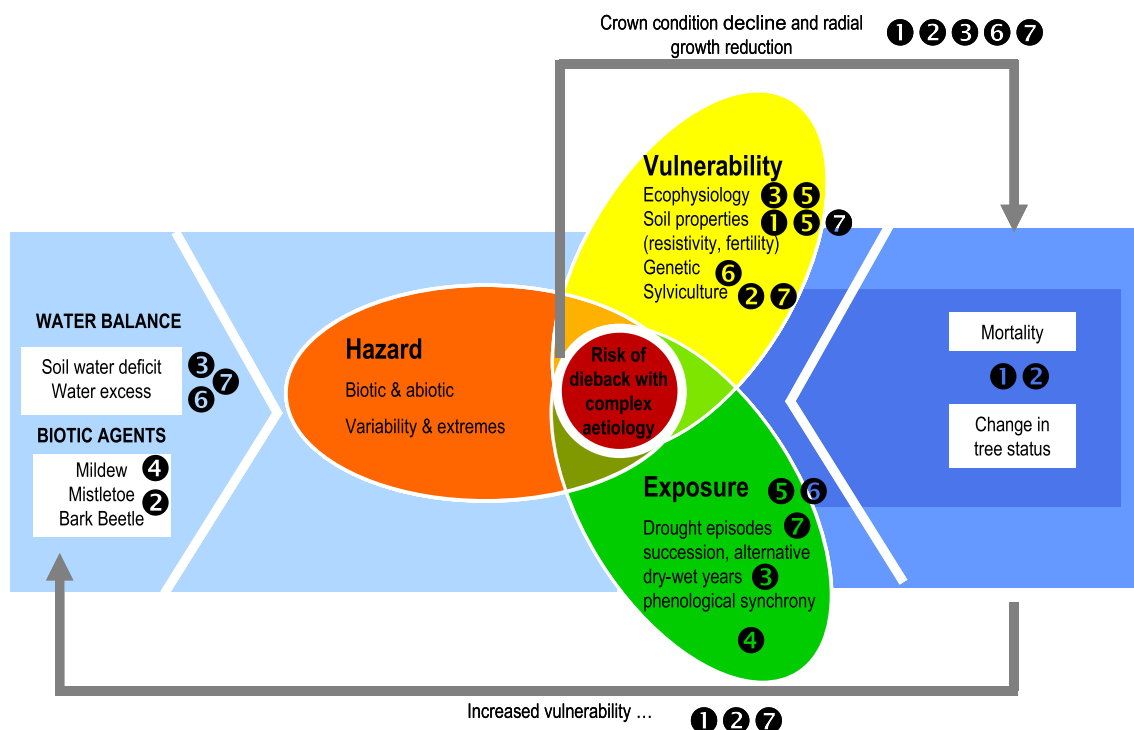


Fig. 1 Scheme of how exposure to climatic or biotic hazard of vulnerable forest stands and trees could result a risk of forest dieback, in most cases with a complex aetiology. Adapted from the core concepts of SREX report (IPCC 2012). Several components of vulnerability have been investigated in the Dryade project. Impacts on growth, health status and mortality were analysed to disentangle hazards, exposure and

determinants of vulnerability. The papers gathered in this special issue are identified in the figure according to the main component(s) of risk addressed. ①: Cailleret et al. 2014, ②: Durand-Gillmann et al. 2014, ③: Gérard and Bréda 2014, ④: Marçais and Desprez-Loustau 2014, ⑤: Nourtier et al. 2014, ⑥: Sergent et al. 2014a, ⑦: Sergent et al. 2014b

the extreme event. Individual vulnerability was assessed using sapwood width, radial growth and wood micro-density.

In the context of an increase of the occurrence of episodes of extreme water deficit, our findings suggest that the best performing trees were the most vulnerable to extreme drought events. Then, the following question was: which tradeoffs between growth performance and sustainability are the most appropriate to cope with extreme events? Taking into account the long term, because growth performance in the young age seemed to be an indicator of higher vulnerability at maturity, appeared essential in this reflection. Carbon allocation strategies among functions (growth, development reserves, fruiting) and among tree compartments (balance between above- and below-ground biomass) were also prospected as functional causes of vulnerability. Should the decline be regarded as a selective force directed against the best performing trees (Guttschick and BassiriRad 2003)? If this was the case, the basics for a silviculture favouring the trees with the highest growth rate would be seriously challenged.

Our findings also confirmed the challenging need for progress in describing and recording dieback events of

dieback. The networks of the national inventory and of forest health monitoring were invaluable for our research. Their maintenance in the long-term needs more than ever to be guaranteed. But at the management level, the registration of phenomena is heterogeneous, partial and difficult to mobilize. We recommend formalizing this work through enhanced monitoring, memory of abnormal phenomena in support of future research work. This record should be regarded as an action towards adaptive management (Spittlehouse 2005). In a context of uncertainty about future climate and biotic disturbances, our results open up avenues to reduce the risk of dieback by management actions and selection of suitable tree species or provenances or silvicultural scheme, to both reduce the vulnerability of future stands and mitigate the intensity of water deficits. A variety of management options needs to be imagined right now in every situation recognized as vulnerable to improve the resilience of ecosystems and secure their long-term management (Bodin and Wiman 2007). To cope with adverse impacts of hazards especially in the most vulnerable situations, adaptive management by anticipation, consisting in forest renewal with species more drought resistant, seems preferable to reactive adaptation, namely crisis management of forest decline when they happen.

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