ECOLOGY

Drought and dead trees

Drought has emerged as a major threat to the world's forests. A study shows that tree mortality in Canada's boreal forests has increased by nearly 5% per year — much higher than expected — owing to water stress from regional warming.

Richard Birdsey and Yude Pan

As forests grow to maturity, trees die from competition for light and nutrients, insects and diseases, disturbance events such as wildfires or windstorms, and human activities such as land-use change and timber harvest. In many regions, warmer temperatures and decreased water supply during recent decades have caused increasing drought stress, which not only has a direct impact on tree survival, but also interacts with other forest stressors, especially wildfire and insects. Writing in *Nature Climate Change*, Peng and colleagues[1] report that over the past 50 years, tree mortality in Canada's boreal forests increased much more than expected over large areas that are unaffected by other observed stressors.

If projections of a warmer and possibly drier climate are realized over the next century, massive tree mortality is a likely consequence, with major impacts on many of the values society places on forests, such as timber, recreation, wildlife habitat, watershed protection and reduction in atmospheric carbon dioxide concentration.

Based on an analysis of long-term data from Canada's boreal forests, Peng and colleagues[1] found that annual mortality rates increased from less than 0.5% per year to values as high as 4.0% per year, with a significantly greater increase in Western Canada. This study and other recent reports of widespread drought-induced tree mortality[2] suggest that the world may already be entering a new era of tree death and forest transformation — processes that will reduce the contribution of forests in removing anthropogenic carbon dioxide emissions from the atmosphere. This could lead to further acceleration of the rate of increase in atmospheric carbon dioxide concentration and potentially even more drought stress for forests.

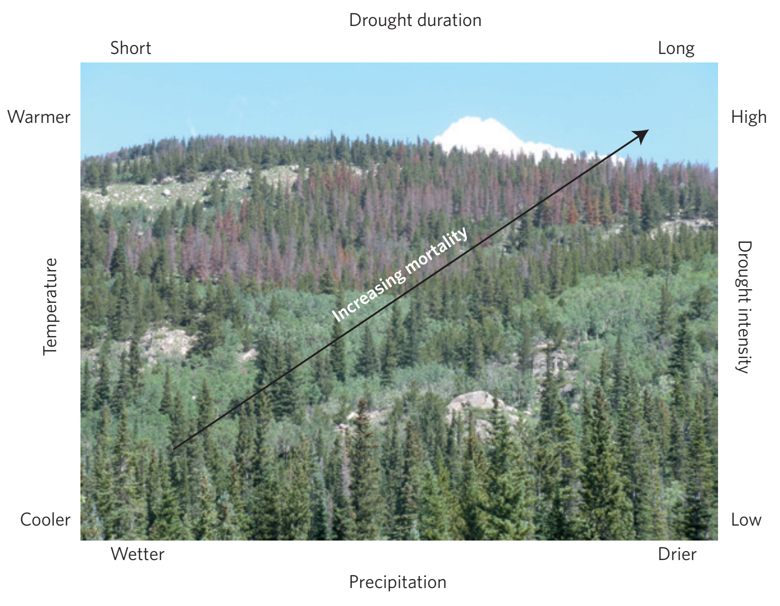

Figure 1 | Conceptual schematic showing how tree mortality might vary with temperature, drought duration and intensity, and precipitation. Figure adapted with permission from ref. 2, © 2010 Elsevier.

A recent analysis of inventory data of the world's forests[3] revealed a significant increase in the mass of carbon accumulating in the dead wood of boreal forests, mainly because of tree mortality from insects and wildfires. The study by Peng and colleagues[1] highlights the role of moisture deficiency as a contributor to increasing mortality by examining forests unaffected by wildfire or outbreaks of insects. Analysis of long-term tree recruitment and mortality data identified systemic changes in tree demography and attributed these observed changes to climate variables.

The study used data from repeated measurements of undisturbed natural forests that were more than 80 years old and composed of trees of all ages and size classes. This approach 'factored out' transient dynamics associated with successional demographics and disturbance events, leaving environmental change as the most likely cause of the observed changes in tree mortality. The analysis revealed significant increases in tree mortality in 83% of the sampled plots for all tree sizes, at all elevations, and for the four most dominant tree species — trembling aspen (*Populus tremuloides*), jack pine (*Pinus banksiana*), black spruce (*Picea mariana*) and white spruce (*Picea glauca*). There were no similar significant increases in tree recruitment. Further analysis revealed that regional warming and the resulting moisture deficit was the most likely cause of the observed increases in tree mortality, especially in Western Canada.

A weakness of using long-term observations to infer causes of effects is that, unlike controlled experiments, it is impossible to rule out other factors that may be significant. For example, calcium deficiency is known to increase susceptibility of red spruce (*Picea rubens*) to winter injury and mortality in forests of the northeastern United States[4]. Nonetheless, the conclusions of Peng and colleagues[1] are supported by both known mechanisms that cause tree death from moisture deficiency, and by other studies reaching similar conclusions about the effects of drought.

A recent review[5] of the mechanisms underlying climate-driven vegetation mortality concluded that hydraulic function and metabolism have numerous failure points that could be triggered by drought and warming temperatures. A previous study of tree mortality in the Western United States[6] using the same approach as Peng and colleagues[1] revealed a widespread increase of tree mortality over recent decades. The authors also attributed mortality to regional warming and water deficits causing widespread hydrologic changes, such as earlier spring snowmelt and runoff, and lengthening of the summer drought. A study conducted in Western Canada[7], in the transition zone between boreal forest and prairie, found extensive patches of dieback and high mortality of trembling aspen correlated with an exceptionally severe drought during 2001–2002. Recent studies of Amazonian forests[8] have also shown the impacts of drought on forests to be significant. Taken together, these and other studies show the current and prospective global importance of drought-induced tree mortality.

In addition to direct effects, climate change has indirect impacts on mortality rates. For example, temperature increase has been linked to increases in bark beetle (*Dendroctonus rufipennis*) outbreaks[9], and moisture deficiency has been associated with increasing wildfire frequency and size[10]. Tree mortality events have considerable, long-lasting and possibly unpredictable impacts. Dead wood may persist in ecosystems for decades, slowly releasing stored carbon and changing the net balance of carbon exchange between terrestrial systems and the atmosphere, and altering the risk of wildfire[11]. Analysis of the carbon budget of Canadian forests[12] has clearly shown that mortality from increasing insect disturbances has and will continue to alter the nation's forest carbon dynamics, decoupling the historical relationship between wildfire and carbon exchange with the atmosphere. Perhaps of even more concern is the unpredictability of forest regeneration after tree mortality events, which has obvious and notable effects on the composition of future forests, or if damaged forests are succeeded by grasslands.

The possibility of a warmer, drier terrestrial climate bodes ill for future forests (Fig. 1). Improved global observations of forests by remote sensing and field measurements could rapidly assess rates of changes in forest characteristics and facilitate adaptation responses such as assisted regeneration. Improved predictive models would help anticipate the impacts of changing terrestrial conditions and allow time for society to adjust to potentially rapid changes in the services we depend on from forests. ❐

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Published online: 20 November 2011

ENERGY

Boosting biofuel yields

Biofuels could be an important energy source, but they compete with food for cropland. An analysis of current crop production suggests that increasing yields of biofuel crops on existing cropland could avoid agricultural expansion and its associated impacts.

Joseph Fargione

Biofuels are a renewable energy source that can partially replace fossil fuels, but their production requires large amounts of land per unit of energy obtained[1]. Consequently, greenhouse-gas emissions from land-use change mean that biofuels are likely to contribute to — rather than mitigate — climate change, if they are associated with conversion of natural ecosystems to biofuel crops[2]. In principle, producing higher yields of biofuel crops on land already dedicated to their growth could reduce this problem, but is it possible to dramatically improve the yields? Writing in *Environmental Research Letters*, Johnston and colleagues[3] show that globally, increased yields could produce an extra 112.5 billion litres of ethanol and 8.5 billion litres of biodiesel on existing cropland.

Data on the actual yields achieved by farmers throughout the world reveal strong variations. When farmers achieve lower than potential yields, agronomists refer to this as a 'yield gap'. The most notable aspect of yield gaps is how large they are. For example, previous yield-gap studies estimate that globally we could produce 50% more maize, nearly 40% more rice, 20% more soybean and 60% more wheat on existing agricultural land simply by closing yield gaps[4]. Of course, the challenge with comparing empirical yield data across different geographic regions is that it is difficult to separate the effects of climate from other effects that farmers can directly control.

Johnston and colleagues[3] address this challenge with a global climate-matching exercise that identifies the highest yields observed for biofuel crops globally in each of 100 climate zones, based on soil moisture availability and growing degree-days. For example, if locations in Brazil and Indonesia fall into the same climate zone (because they have similar growing degree-days and soil-moisture availability), then those two climates