Altered dynamics of forest recovery under a changing climate

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Forthcoming, *Global Change Biology*

Background

- Climate change can alter the dynamics of forest recovery following disturbance; however, **we lack synthetic understanding of how forest recovery will respond to climate change**.
- We review five lines of evidence relating forest structure and function to directional variation in CO_2 and climate, each of which yields insight into how forest recovery may be altered under a changing climate.

Dynamics of Forest Recovery Across Broad Climatic Gradients

- ***Climate shapes the rate of recovery***
  - Globally, the **rate of biomass accumulation** following disturbance increases with mean annual temperature and precipitation (Fig. 1A,B).
  - Likewise, **rates and trajectories of community change** are strongly influenced by climate.
- ***Climate shapes the conditions to to which forests can eventually converge***
  - Aboveground biomass (Fig. 1C,D) and other ecosystem properties are constrained by temperate and precipitation on a global scale.

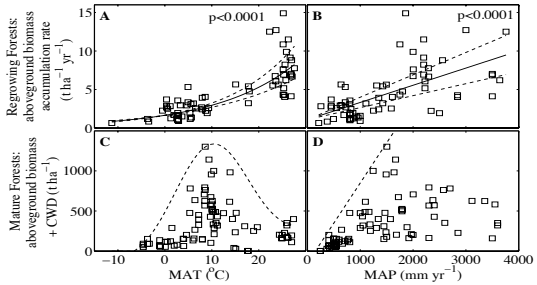

Figure 1. Influence of climate on forest recovery rates (A, B) and on the biomass of mature forests (C, D). The rate of aboveground biomass accumulation in forests recovering from stand-clearing disturbance varies globally with respect to (A) mean annual temperature and (B) precipitation. Data, which are from Anderson et al. (2006), represent natural regeneration in 68 unmanaged forests worldwide. Solid and dashed lines represent an exponential fit and its 95% confidence interval, respectively. Similarly, aboveground C stocks (biomass + coarse woody debris; CWD) in mature forests vary globally with respect to (C) mean annual temperature and (D) precipitation. Data from Anderson-Teixeira et al. (2011). Dashed lines represent hypothesized bioclimatic limits.

Altered Forest Recovery under Contemporary Multivariate Environmental Change

- Tree-ring and observational records extending back decades to centuries demonstrate **that forest productivity is strongly shaped by climate**.
- Comparison of chronosequence biomass-age relationships with current biomass accumulation rates in forests of various age suggests **accelerated regrowth of some moist temperate forests following stand-clearing disturbances** (Fig. 2).
- There is evidence that **some forests are not returning to their previous state** following stand-clearing disturbance as a result of climate change.

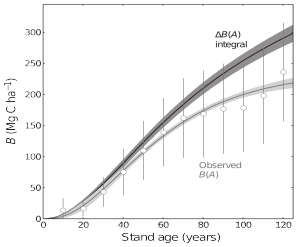

Figure 2. Evidence of accelerated forest growth in a coastal fir-hemlock forest in British Columbia, Canada. Plotted are observed stemwood biomass (B) as a function of forest age ("Observed B(A)"; grey line) and the stemwood biomass that would be predicted based upon recent rates of stemwood production ("ΔB(A) integral"; black line). Shading marks 95% confidence intervals. Importantly, the integrated increment surpasses observed biomass, indicating that effects of climate change have increased biomass production (~58%). Because this discrepancy is greater in older forests, there is potential for long-term increase in NPP and carbon stocks in this region. Modified from Hember et al. (2012).

Abstract. Forest regeneration following disturbance is a key ecological process, influencing forest structure and function, species assemblages, and ecosystem-climate interactions. Climate change may alter forest recovery dynamics or even prevent recovery, potentially triggering feedbacks to the climate system, altering regional biodiversity and affecting the ecosystem services provided by forests. Multiple lines of evidence—including global-scale patterns in forest recovery dynamics; forest responses to experimental manipulation of CO_2, temperature, and precipitation; forest responses to the climate change that has already occurred; ecological theory; and ecosystem and earth system models—all indicate that the dynamics of forest recovery are sensitive to climate. However, synthetic understanding of how forest recovery will respond to increased atmospheric CO_2 and climate change is lacking. We review these separate lines of evidence, which together demonstrate that the dynamics of forest recovery are being impacted by increasing atmospheric CO_2 and altered climate. Forest regrowth rates generally increase with CO_2, temperature, and precipitation, but it remains unclear whether growth stimulation can be sustained as forests age. Drought generally reduces growth and live biomass in forests of all ages, and has a particularly strong effect on seedling recruitment and survival. Although CO_2 and climate responses often vary by age, underlying mechanisms remain poorly understood. Furthermore, species within a community typically exhibit differential responses to CO_2 and climate, and understanding the role of altered community dynamics in driving ecosystem function remains an important challenge. Age- and species-dependent responses imply that climate change may push some forests past critical thresholds such that they fail to recover to their previous state following disturbance, yet such responses remain difficult to predict. Future research on this topic and corresponding improvements to earth system models will be key to understanding the future of forests and their feedbacks to climate.

Forest Responses to Experimental Manipulation of CO_2, Temperature, and Precipitation

- **Experiments manipulating CO_2, temperature, and precipitation demonstrate that altered climatic conditions will change ecosystem and community dynamics in secondary forests.**
- *Elevated CO_2*
  - **Elevated CO_2 stimulates NPP in young forests—at least initially—but it is uncertain whether such stimulation is possible in mature forests** (Fig. 3).
  - The ability of forests to sustain increased NPP under elevated CO_2 as they age—and, ultimately, the potential for mature forests to increase C storage under elevated CO_2(Fig. 3)—depends in large part upon biogeochemical feedbacks.
  - **Responses to elevated CO_2 are variable among species and size classes**, implying altered successional dynamics.

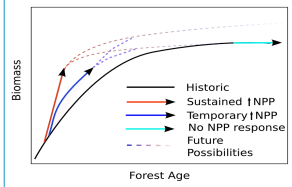

Figure 3. Schematic diagram showing three example responses of forests to experimental manipulation. Solid black line shows the historical relationship between biomass and forest age. Solid colored lines represent observed experimental responses: a sustained NPP stimulation, a temporary NPP stimulation, and no NPP stimulation. Dashed lines represent alternative potential long-term responses: one where NPP stimulation causes forests to reach maximum biomass more rapidly without increasing final biomass and one where final biomass is increased.

- *Warming*
  - **Soil warming increases belowground metabolism and soil respiration while increasing aboveground growth. Air warming may alter the response**.
  - The relationship between forest age and responses to warming is unclear.
  - **Responses to warming are variable among species and size classes**, implying altered successional dynamics.
- *Altered Precipitation*
  - Across a range of climates and forest ages, **tree growth and survival, productivity, and soil respiration are generally increased by water addition and reduced by water removal** (except in very wet climates).
  - **Responses to precipitation are variable among species and size classes**, implying altered successional dynamics, portending future changes to community composition under altered precipitation regimes.

Community Dynamics and the Potential for State Changes

- **Climate change will alter species community dynamics** (1) directly by altering the physical environment in which species of varying physiological strategies are competing and (2) indirectly by altering the disturbance regime.
- **Changes in community composition driven by altered climate and disturbance regimes may have dramatic consequences for ecosystem functioning**.
- In some cases, **climate change may push forests past a critical threshold such that, upon perturbation, they undergo a catastrophic shift and fail to return to their previous state** (Fig. 4).

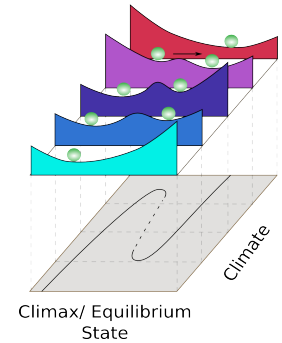

Figure 4. Schematic diagram illustrating the potential for disturbance to push ecosystems from one stable state to another as the climate changes. Colored shapes represent the "landscape" of stable ecosystem states under different climate regimes, and balls represent states in which ecosystems can stably exist—in this case, the "climax" stage of succession. The diagram below illustrates a hysteresis, where alternate stable states exist. As the climate shifts, basins of attraction shift such that the stable climax stage eventually shifts from one state to the other. During the transition, however, disturbance (indicated by black arrow) may hasten the shift from one stable state to another. Modified from Scheffer et al. (2001).

Ecosystem and Earth System Model Projections

- **Uncertainties regarding the responses of secondary forests to climate change challenge our ability to accurately represent them models**, which are currently simplistic in their treatment of forest recovery dynamics.
- Models pay little to no attention to the demonstrated importance of differential species responses and and ecosystem-level consequences of community dynamics.
- Despite their uncertainties, **models have demonstrated that forest recovery is likely to be substantially altered under future climates.**
- **Simulated climate change effects on forest growth vary by region and model**, with expected increases in forest productivity in some regions and decreases in others.

Conclusions

- **Increasing CO_2, warming, and altered precipitation regimes alter the dynamics of forest regeneration, with important consequences for biodiversity and climate change feedbacks.**
- **Uncertainty remains regarding the near-term responses of many forests (particularly tropical) and the long-term responses of all forests.**
- **Responses to climate change likely vary with forest age. Systematic analysis will be crucial to understanding and modeling climate change impacts on forests.**
- **Differential species responses and altered successional dynamics may have enduring impacts on community composition and ecosystem function.**
- **Regime shifts that prevent forests from recovering to their previous state following disturbance (Fig. 4) will have particularly dramatic consequences.**
- **Because disturbance eventually affects all forests, the proportion of forests that have regenerated under altered climate conditions will steadily grow, and climate change will broadly impact forested regions through its influence on forest recovery dynamics.**

Acknowledgments

- Funding: DOE grant #DE-SC0008085 to KJAT, EHD, and BDD
- Helpful discussion: Jonathan Thompson, Sean McMahon