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Disturbance Distance: quantifying forests' vulnerability to disturbance under current and future conditions

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Abstract

Disturbances, both natural and anthropogenic, are critical determinants of forest structure, function, and distribution. The vulnerability of forests to potential changes in disturbance rates remains largely unknown. Here, we developed a framework for quantifying and mapping the vulnerability of forests to changes in disturbance rates. By comparing recent estimates of observed forest disturbance rates over a sample of contiguous US forests to modeled rates of disturbance resulting in forest loss, a novel index of vulnerability, Disturbance Distance, was produced. Sample results indicate that 20% of current US forestland could be lost if disturbance rates were to double, with southwestern forests showing highest vulnerability. Under a future climate scenario, the majority of US forests showed capabilities of withstanding higher rates of disturbance then under the current climate scenario, which may buffer some impacts of intensified forest disturbance.

While climate attributes such as temperature and precipitation are principal determinants of the distribution of the world's ecosystems (i.e. tundra vs. forestland), natural disturbances such as fire, wind, and other events can also influence the distribution and properties of ecological systems [1]. Within forested ecosystems, disturbance influences forest structure, function and composition, and thus the ecosystem services they provide [2–5]. Recent studies have highlighted changes in natural disturbance regimes compared to historic norms and the potential for further alterations in disturbance regimes from future climate change on a scale unprecedented in historic records [6–13]. These studies lead to a key question: What levels of disturbance can forests tolerate before they face critical alterations in structure and function and how might their sensitivity to disturbance change under future climate?

While field studies that characterize and/or simulate the impact of disturbance continue to be vital to our understanding of changing disturbance impacts to forested ecosystems, it is difficult and often impractical to extend these studies to continental and centennial scales [14, 15]. Thus, process-based prognostic models that can simulate events over larger areas and temporal scales have been used to advance our understanding of regional to global ecosystem dynamics. Previous studies have explored a range of topics such as the modification of global vegetation in a world without fire, to the potential impacts of large-scale deforestation in Tropical and Boreal regions, to the dependence of future climate mitigation stategies on the future rate of natural disturbance rates [1, 16–18].

Given the critical roles disturbance plays in shaping forest structure, function, and dynamics, we propose a framework to assess ecosystem vulnerability to disturbances. Specifically, we sought to address the following questions: (1) What is the maximum rate of disturbance for which current forests can be maintained across the US?; (2) How close are current forests to a fundamental shift in ecosystem structure?; and, (3) How may forest

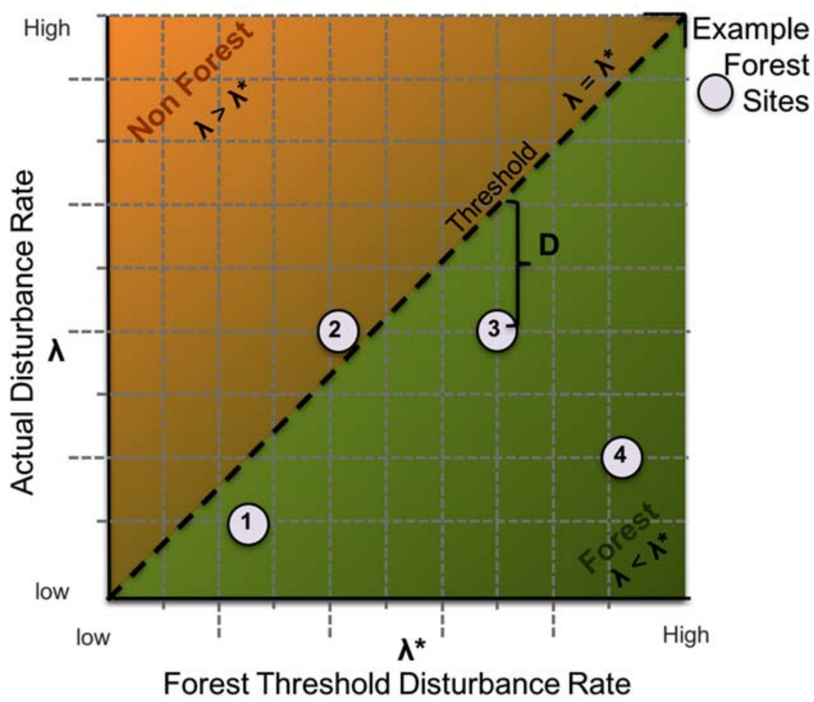

Figure 1. Conceptual diagram of Disturbance Distance (*D*). Given unique environmental growing conditions, forests tolerance to disturbance (λ^* *x*-axis) varies from low in areas with poor growing conditions (site-1 and 2) to high in areas with favorable growing conditions (site-3 and 4). At the same time forests sites vary in the actual rates of disturbance experienced (λ) from relatively lower rates of disturbance (sites 1 and 4) to higher rates (sites 2 and 3). Subtracting actual rates of disturbance from an ecosystems threshold rate gives an indication of the additional amount of disturbance a forest can tolerate (*D*) before a transition to non-forest occurs.

ecosystem sensitivity to disturbance change under a potential future climate change scenario?

Forest vulnerability to disturbance was determined by developing a simple and flexible framework. First, ecosystem responses to disturbance are evaluated under representative climatic and environmental conditions to determine threshold rates of disturbance (λ^*), the rates that lead to fundamental alterations of vegetation structure (i.e. transition from forest to non-forest based on criteria of plant structure, composition and biomass). While forests with favorable growing conditions recover faster and can thus tolerate higher disturbance, the same level of disturbance on a site with poor growing conditions can be enough to tip the land into a different ecosystem type [19]. Next, estimates of actual forest disturbance rates (λ) are acquired over forested regions. Comparing these observed rates of disturbance to the estimated threshold rates provide estimates of how much additional disturbance an ecosystem may tolerate before a transition threshold is reached, herein termed Disturbance Distance (equation (1))

$$D = \lambda^* - \lambda. \quad (1)$$

A region's Disturbance Distance, *D*, gives insight into its vulnerability to potential increases in disturbance intensity (figure 1).

In this report, threshold disturbance rates (λ^*) for which forest conditions could be maintained across the contiguous US were estimated by simulating potential vegetation growth and dynamics under varying disturbance rate scenarios in an advanced mechanistic and prognostic ecosystem model [20] (see methods supplement available at stacks.iop.org/ERL/12/114015/mmedia). Following previous studies [3, 21] the forest threshold definition used here, required the maintenance of forest plant functional types and an above ground standing stock of natural cover equivalent to 2 kgC m^{-2} or greater. While the individual-based mechanistic model was chosen in part due to its capabilities to incorporate sub-models of disturbance that may allow future studies of disturbance interactions and feedbacks [3, 22], to isolate the average disturbance rate leading to non-forest conditions, all sub-models were turned off and annual disturbance rates were held constant in time and space within each model run. The modeled-based results of this simplified disturbance case study indicate that forests in southeastern US can maintain the highest rates of disturbance before non-forest conditions are reached, while southwestern forests were estimated to have the lowest disturbance rate thresholds (figure 2).

To estimate how far current forests may be from a transition to non-forest, threshold rates of disturbance (λ^*) were compared to remotely sensed derived estimates of disturbance over 50 US forested Landsat scenes representative of major forest types [23]. The observed average annual disturbance rates (λ), measured as the percent of live forest cover loss persisting 2 or more years between 1986–2010, ranged from 0.4%–3.8% yr^{-1} with a national average of 1.4% yr^{-1} (figure 2, figure S1). Over these same forested

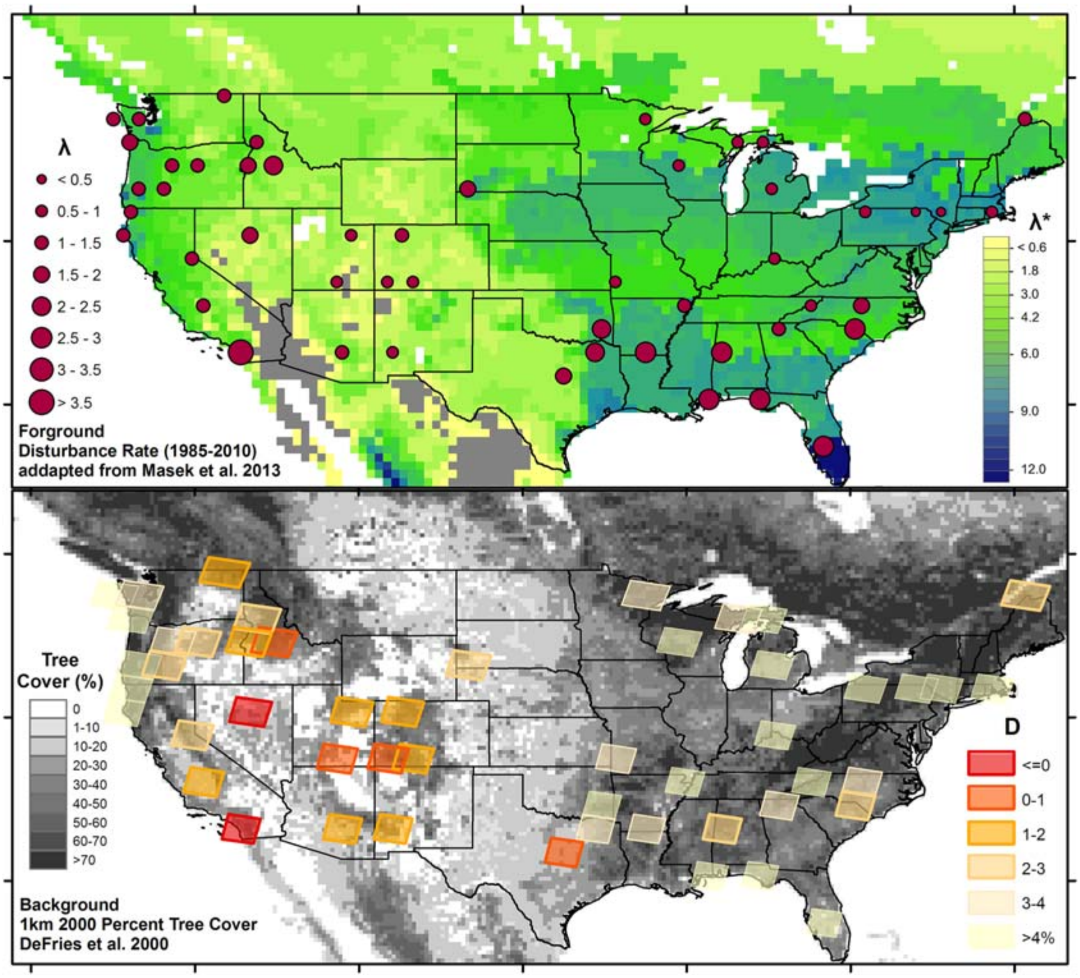

Figure 2. Top panel shows the geographic variation in estimated threshold disturbance rates, (λ^*) (% yr^{-1}), under 20th century climate conditions, overlaid by mean annual observed disturbance rates, (λ) (% yr^{-1}) at 50 NAFD sample forested regions from Masek *et al* 2013. The Disturbance Distance (D), or increase in mean observed disturbance rates (λ) that would lead to non-forest conditions for the 50 sample forest regions is shown in the bottom panel. An independent layer of tree cover percent provides spatial reference of current forest distribution.

scenes, under 20th century climate conditions, average threshold rates of disturbance (λ^*) ranged from ~1.5%–12% yr^{-1} (figure 2). In general, Disturbance Distances were estimated to be much smaller across western forests (west of 100 W) with nearly half the western sites estimated to transition to non-forest if an additional 2% of forest area was disturbed annually, while only one eastern forested site showed this same vulnerability (figure 2, figure S2). In a scenario where current disturbance rates double, and assuming the 50 Landsat scenes are representative of US forests, ~20% or 51 million hectares of forests would be exposed to disturbance-induced transitions to non-forest ecosystems (figure 4, figure S3), while the timing of transition will vary in part due to rate of disturbance and recovery.

Vegetation growth and response to disturbance will change under future climate conditions. To evaluate how forests' sensitivity to disturbance may change in the future, the threshold rates of disturbance were estimated under a representative future climatology from the North American Regional Climate Change Assessment Program (NARCCAP) which is based off the IPCC A2 emissions scenario [24] (see methods supplement). The estimated thresholds rates under the future climate scenario, were again compared to the remotely observed disturbance rates, to estimate forests' Disturbance Distance under a future climate scenario. The resulting Disturbance Distances (D) were higher over the majority of sites (figure 3), suggesting an overall decrease in vulnerability to increased disturbance rates under this specific future scenario. Only 15% of all sampled forest scenes showed a decline in tolerance to disturbance, and the share of forests susceptible to loss if current disturbance rates were to double was reduced by ~50% (figure 4, figure S4). The southern California site stands out as an extremely vulnerable outlier, as the disturbance distance was slightly negative under 20th century climate and decreased further in the future scenario. Conversely, northwestern forests showed the largest potential to decrease vulnerability under the future climate scenario. Overall, we estimated the majority of US forests will be able to tolerate higher rates of disturbance under a future climate scenario than under a contemporary climate (figure 4).

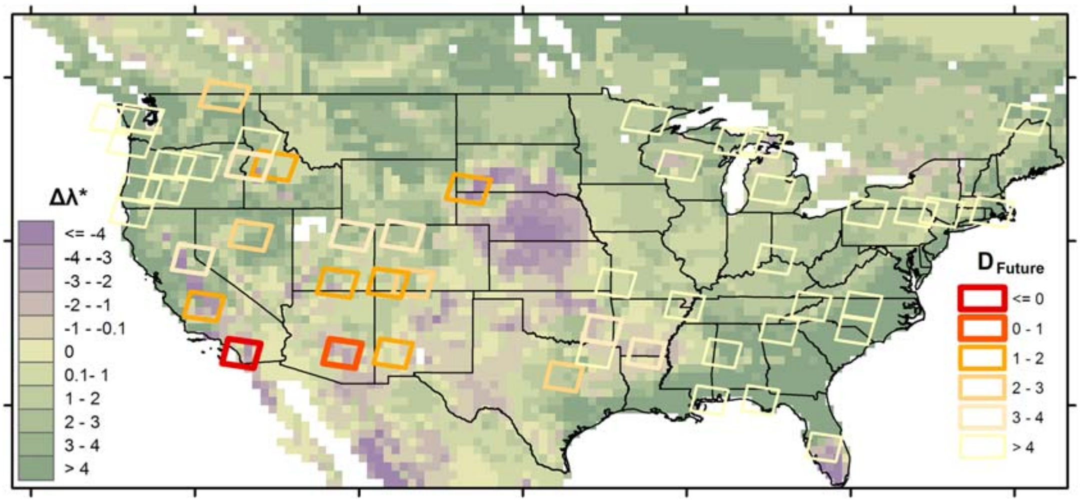

Figure 3. Change in threshold rates estimated under a future A2 climate scenario across the US are overlaid with the corresponding increase in observed mean disturbance rates (1986–2010) that would lead to non-forest conditions for the 50 sample forest regions under the future climate scenario (*D*).

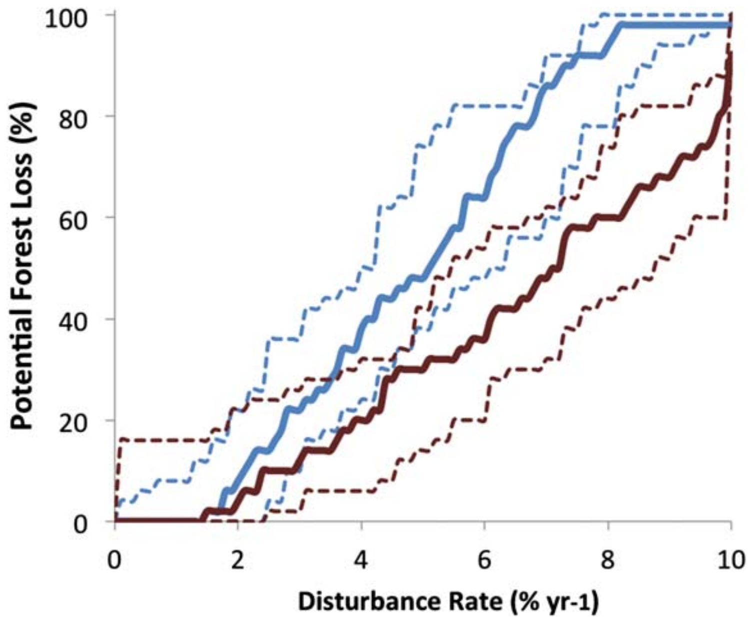

Figure 4. Estimated US forest loss under current (blue) and future (red) climate conditions, when exposed to a range of disturbance rates. Estimates of loss are bounded by the upper and lower growing conditions (dotted lines) within the Landsat scenes.

Projected changes in future climate and disturbance regimes have heightened the need for continued research on forest disturbance and ecosystem response monitoring and modeling capabilities. Here we used an advanced ecosystem model to estimate a novel metric, disturbance rate threshold, which measured the highest rates of disturbance that can be tolerated before non forest conditions persist across the diverse climatic and edaphic gradients found within the continental US. Comparing this metric to measured rates of forest disturbance across the US quantified patterns of forest vulnerability to altered rates of disturbance. This study thus provides a preliminary baseline and flexible framework that can be applied to additional regions and adapted to specific research objectives. Our case study focused on transitions to non forest, but before non forest conditions are met changes in disturbance rates are likely to cause other important structural and functional ecological modifications such as changes in species composition, carbon sequestration potential, basal area, and forest height [14, 15, 19, 25–27]. This framework could provide guidance on management interventionto ease the transition to new and better adapted forest states [28], and may identify areas that have not been historically defined as forests, but have the potential to sustain them if disturbances such as grazing and/or fire were suppressed below critical threshold rates [1 , 29].

This case study highlights the differences in forest vulnerability to altered disturbance rates across the US. Results show most forested regions can withstand higher disturbance rates than the average rates detected by remote sensing and that most US forests will be able to withstand higher rates of disturbance in the future. Many complex and non-linear interactions between climate, soils and atmospheric CO_2 concentrations effect vegetation growth, mortality and competition [11, 30–32]. Thus as climate and edaphic conditions vary across the US so do the variance in the magnitude and direction of change in vulnerability to disturbance. In particular, this study suggests some forested areas, particularly water-limited areas of the western US, could become more vulnerable to increases in disturbance rates under an IPCC A2 climate scenario. This finding is aligned with several recent papers documenting increased mortality in western forests arising from decreased water availability driven by warmer and drier conditions [9, 13, 33]. The finding that the majority of the contiguous US forests may become less vulnerable to disturbance under a future climate scenario coincides with previous studies that have shown enhanced productivity stimulated by increases in CO_2 and temperature [34–36], although sustained enhancement of vegetation to CO_2 has been questioned [37–39]. Our study does not attempt to project what future disturbance rates will be and it is very conceivable that disturbance rates (i.e more frequent fires, intense storms and pest and pathogen outbreaks) could increase at levels that limit any projected gains in recovery potential from climate change [6, 10–12, 40]. Currently beyond the scope of our present study, we suggest incorporating more disturbance and climate change scenarios into the modeling framework, to better quantify the range of vegetation response to altered disturbance and encourage continued model inter-comparisons to test vulnerability under a range of ecological assumptions [41–45]. More detailed investigations of ecosystem health and impact, adaptation and vulnerability studies (IAV) are needed.

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