LETTER • OPEN ACCESS

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

To cite this article: Katelyn A Dolan et al 2017 Environ. Res. Lett. 12 114015

View the article online for updates and enhancements.

Related content

- Operational approaches to managing forests of the future in Mediterranean regions within a context of changing climates
  Scott L Stephens, Constance I Millar and Brandon M Collins

- Assessing climate change impacts, benefits of mitigation, and uncertainties on major global forest regions under multiple socioeconomic and emissions scenarios
  John B Kim, Erwan Monier, Brent Sohngen et al.

- Are forest disturbances amplifying or canceling out climate change-induced productivity changes in European forests?
  Christopher P O Reyer, Stephen Bathgate, Kristina Blennow et al.
Disturbance Distance: quantifying forests’ vulnerability to disturbance under current and future conditions

Katelyn A Dolan1,2, George C Hurtt1, Steve A Flanagan1, Justin P Fisk1,2, Ritvik Sahajpal1, Chengquan Huang1, Yannik Le Page1,3, Ralph Dubayah1 and Jeffrey G Masek4

1 Department of Geographical Sciences, University of Maryland, College Park, MD, United States of America
2 Applied Geosolutions, 87 Packers Falls Road, Durham, NH, United States of America
3 Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisbon, Portugal
4 Biospheric Sciences Laboratory NASA Goddard Space Flight Center, Greenbelt, MD, United States of America
5 Author to whom any correspondence should be addressed.

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 than 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 strategies 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 ($\lambda^*$, 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 ($\lambda$) 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.

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 ($\lambda^*$), 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 ($\lambda$) 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))

$$D = \lambda^* - \lambda.$$  

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 ($\lambda^*$) 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 ($\lambda^*$) 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 ($\lambda$), 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 ecosystems 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 ($\lambda^*$), 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 ($\lambda$) 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))

$$D = \lambda^* - \lambda.$$  

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 ($\lambda^*$) 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 ($\lambda^*$) 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 ($\lambda$), 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, \( \lambda^* \) (% yr\(^{-1}\)), under 20th century climate conditions, overlaid by mean annual observed disturbance rates, \( \lambda \) (% yr\(^{-1}\)) at 50 NAFD sample forested regions from Masek et al. 2013. The Disturbance Distance \( (D) \), or increase in mean observed disturbance rates \( \lambda \) 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.

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 \( \sim 50\% \) (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).
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 interventions to 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].

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.
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 CO₂ 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 CO₂ and temperature [34–36], although sustained enhancement of vegetation to CO₂ 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.

Acknowledgments

We gratefully acknowledge the support of the NASA Terrestrial Ecology Program, NASA-CMS, and the NASA Earth and Space Science Graduate Fellowship Program. Partial funding for open access was provided by the UMD Libraries ‘Open Access Publishing Fund’. We thank two anonymous reviewers, and Dr Joe Sullivan for their time and valuable input leading to improvement of this manuscript. We would like to extend a special thanks to Feng Zhao for preparing and providing the most up to date Vegetation Change Tracker (VCT) disturbance results associated with Masek et al 2013. Access and information on the Ecosystem Demography Model and code can be found at http://gel.umd.edu/ed.php.

ORCID IDs

Katelyn A Dolan @ https://orcid.org/0000-0002-1119-2277

References

[1] Bond W J, Ian Woodward F and Midgley G F 2005 The global distribution of ecosystems in a world without fire New. Phytol. 165 525–38
[2] Frolking S, Palace M W, Clark D B, Chambers J Q, Shugart H H and Hurt G C 2009 Forest disturbance and recovery: a general review in the context of spaceborne remote sensing of impacts on aboveground biomass and canopy structure J. Geophys. Res. Biogeosci. 114 G00E02
[3] Hurt G C, Pacala S W, Moorcroft P R, Caspersen I, Shvidakova E, Houghton R A and Moore B 2002 Projecting the future of the US carbon sink Proc. Natl Acad. Sci. 99 1389–94
[4] Lorimer G C and White A S 2003 Scale and frequency of natural disturbances in the Northeastern US: implications for early successional forest habitats and regional age distributions Forest Ecol. Manage. 185 41–64
[5] Oliver C D et al 1996 Forest Stand Dynamics: Updated Edition (New York: Wiley)
[6] Dale V H et al 2001 Climate change and forest disturbances BioScience 51 725–34
[7] Kurz W A, Dymond C C, Stinson G, Rampley G J, Neilson E T, Carroll A L, Ebata T and Safyaník I. 2008 Mountain pine beetle and forest carbon feedback to climate change Nature 452 987–90
[8] Zeng H, Chambers J Q, Negrón-Juárez R I, Hurt G C, Baker D B and Powell M D 2009 Impacts of tropical cyclones on US forest tree mortality and carbon flux from 1851 to 2000 Proc. Natl Acad. Sci. 106 7888–92
[9] Allen C D et al 2010 A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests Forest Ecol. Manage. 259 660–84
[10] Bentz B J, Régnière J, Fettig C J, Matthew Hansen E, Hayes J L, Hicke J A, Kelsey R G, Negrón J F and Seybold S J 2010 Climate change and bark beetles of the western united states and canada: direct and indirect effects BioScience 60 602–13
[11] Seidl R et al 2017 Forest disturbances under climate change Nat. Clim. Change 7 395–402
[12] Trumbore S, Brando P and Hartmann H 2015 Forest health and global change Science 349 814–8
[13] Cohen W B, Yang Z, Stehman S V, Schroeder T A, Bell D M, Masek J G, Huang C and Meigs G W 2016 Forest disturbance across the conterminous united states from 1985–2012: the emerging dominance of forest decline Forest Ecol. Manage. 360 242–52
[14] Rogers P 1996 Disturbance ecology and forest management: a general review in the context of spaceborne remote sensing of impacts on aboveground biomass and canopy structure J. Geophys. Res. Biogeosci. 114 G00E02
[15] Reyer C P O et al 2015 Forest resilience and tipping points at different spatio-temporal scales: approaches and challenges J. Ecol. 103 3–15
[16] Shukla J J et al 1990 Amazon deforestation and climate change Science (Washington) 247 1322–5
[17] Bonan G B, Pollard D and Thompson S L 1992 Effects of boreal forest vegetation on global climate Nature 359 716–8
[18] Yannik Le P et al 2013 Sensitivity of climate mitigation strategies to natural disturbances Environ. Res. Lett. 8 015018
[19] Turner M G, Romme W H, Gardner R H, O’Neill R V and Kratz T K 1993 A revised concept of landscape equilibrium: disturbance and stability on scaled landscapes Landscape Ecol. 8 213–27
[20] Moorcroft P R, Hurt G C and Pacala S W 2001 A method for scaling vegetation dynamics: the ecosystem demography model (ED) Ecol. Monogr. 71 557–86
[21] Hurtt G C et al 2011 Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands Clim. Change 109 117

[22] Fisk J P, Hurtt G C, Chambers J Q, Zeng H, Dolan K A and Negron-Juarez R I 2013 The impacts of tropical cyclones on the net carbon balance of eastern US forests 1851–2000 Environ. Res. Lett. 8 045017

[23] Mason J, Gooskens J, Ahlström A, Boisier J P, Goetz S J, Goward S N, Molnár Z E, Masek J G, Harris P and Masek J G 2015 Impacts of disturbance on the terrestrial carbon budget Ecosystems 16 1087–104

[24] Mearns L O, Gutowski W, Jones R, Leung R, McGinnis S, Nunes A and Qian Y 2009 A regional climate change assessment program for North America Eos. Trans. Am. Geophys. Un. 90 311–1

[25] McDowell N G et al 2015 Global satellite monitoring of climate-induced vegetation disturbances Trends Plant Sci. 20 114–23

[26] Kaschek E S, Amirou B D, Barger N N, French N H F, Goetz S J, Grosse G, Harmon M E, Hickie J A, Liu S and Mason J G 2013 Impacts of disturbance on the terrestrial carbon budget of North America J. Geophys. Res. Biogeosci. 118 303–16

[27] Tanagan S A, Hurtt G C, Fish J P, Sahapal R, Hansen M C, Dolan K A, Sullivan J H and Zhao M 2016 Potential vegetation and carbon redistribution in Northern North America from climate change Climate 4 2

[28] Millar C I and Stephenson N L 2013 Temperate forest health in an era of emerging megadisturbance Science 349 623–6

[29] Briggs J M, Knapp A K, Blair J M, LHeisler J, Hoch G A, Lett M S and McCarron J K 2005 An ecosystem in transition: causes and consequences of the conversion of mesic grassland to shrubland BioScience 55 243–54

[30] Meillot I M, Callaghan T V, Woodward F J, Salati E and Simha S 1990 Effects on ecosystems Climate Change: The IPCC Scientific Assessment pages 283–310

[31] Ghanoum O and Way D A 2011 On the role of ecological adaptation and geographic distribution in the response of trees to climate change Tree Physiol. 31 1273–6

[32] Nunes L, Gower S T, Peckham S D, Magoulès M, Lopes D and Rego F C 2014 Estimation of productivity in pine and oak forests in northern Portugal using Biome-BGC Forest Int. J. Forest Res. 88 200–12

[33] Breshears D D et al 2005 Regional vegetation die-off in response to global-change-type drought Proc. Natl Acad. Sci. USA 102 15144–8

[34] Norby R J et al 2005 Forest response to elevated CO2 is conserved across a broad range of productivity Proc. Natl Acad. Sci. USA 102 18052–6

[35] Ido S B and Kimball B A 1993 Tree growth in carbon dioxide enriched air and its implications for global carbon cycling and maximum levels of atmospheric CO2 Glob. Biogeochem. Cycles 7 537–55

[36] Higgins S I and Scheiter S 2012 Atmospheric CO2 forces abrupt vegetation shifts locally, but not globally Nature 488 209–12

[37] Reich P B, Hobbie S E, Lee T, Ellsworth D S, West J B, Tilman D, Knops J M H, Naem S and Trost J 2006 Nitrogen limitation constrains sustainability of ecosystem response to CO2 Nature 440 922

[38] Oren R et al 2001 Soil fertility limits carbon sequestration by forest ecosystems in a CO2-enriched atmosphere Nature 411 469

[39] Warren J M, Norby R J and Wullschleger S D 2011 Elevated CO2 enhances leaf senescence during extreme drought in a temperate forest Tree Physiol. 31 117–30

[40] Liu Z and Wimberly M C 2016 Direct and indirect effects of climate change on projected future fire regimes in the western united states Sci. Total Environ. 542 65–75

[41] Wei Y et al 2014 The north american carbon program multi-scale synthesis and terrestrial model intercomparison project Part 2: environmental driven data Geosci. Model Dev. 7 2875–93

[42] Sitch S et al 2008 Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five dynamic global vegetation models (dgvm) Glob. Change Biol. 14 2015–39

[43] Bond-Lamberty B, Fisk J P, Holm J A, Bailey V, Bohrer G and Gough C M 2013 Moderate forest disturbance as a stringent test for gap and big-leaf models Biogeosciences 12 513–26

[44] Dietze M C et al 2014 A quantitative assessment of a terrestrial biosphere model’s data needs across north american biomes J. Geophys. Res. Biogeosci. 119 286–300

[45] McDowell N G, Beering D J, Breshears D D, Fisher R A, Raffa K F and Sitt T M 2013 The interdependence of mechanisms underlying climate-driven vegetation mortality Trends Ecol. Evol. 26 523–32

[46] Hurtt G C et al 1998 Terrestrial models and global change: challenges for the future Glob. Change Biol. 4 881–90

[47] Batjes N H 2012 Isric-wise derived soil properties on a 5 by 5 arc-minutes global grid Technical Report ISRIC-World Soil Information

[48] Zeller K A, Hurtt G C, Chambers J Q, Dubayah R O, Froliking S and Masek J G 2013 Using icecat’s geoscience laser altimeter system (glas) to assess large-scale forest disturbance caused by hurricane katrina Remote Sens. Environ. 115 86–96

[49] Hurtt G C, Dubayah R, Drake J, Moorcroft P R, Papac S A, Blair J B and Fearon M G 2004 Beyond potential vegetation: combining lidar data and a height-structured model for carbon studies Ecol. Appl. 14 873–83

[50] Thomas R Q, Hurtt G C, Dubayah R and Schim M H 2008 Using lidar data and a height-structured ecosystem model to estimate forest carbon stocks and fluxes over mountainous terrain Can. J. Remote Sens. 34 5351–63

[51] Hurtt G C, Fisk J, Thomas R Q, Dubayah R, Moorcroft P R and Shugart H H 2010 Linking models and data on vegetation structure J. Geophys. Res. Biogeosci. 115 G00E10

[52] Fisk J 2015 Net effects of disturbance: spatial, temporal, and societal dimensions of forest disturbance and recovery on terrestrial carbon balance PhD Dissertation (University of New Hampshire)

[53] Goward S N et al 2008 Forest disturbance and north american forest carbon flux Eos. Trans. Am. Geophys. Un. 89 105–6

[54] Huang C et al 2009 Development of time series stacks of landsat images for reconstructing forest disturbance history Int. J. Digital Earth 2 195–218

[55] Huang C, Goward S N, Mason J G, Thomas N, Zhu Z and Vogelmann J E 2010 An automated approach for reconstructing recent forest disturbance history using dense landsat time series stacks Remote Sens. Environ. 114 183–98

[56] Thomas N E, Huang C, Goward S N, Powell S, Rishmawi K, Schleeweis K and Hinds A 2011 Validation of north american forest disturbance dynamics derived from landsat time series stacks Remote Sens. Environ. 115 19–32

[57] Fisher I J, Hurtt G C, Quinn Thomas R and Chambers J Q 2008 Clustered disturbances lead to bias in large-scale estimates based on forest sample plots Ecol. Lett. 11 554–63

[58] Schleeweis K, Goward S N, Huang C, Mason J G, Moisen G, Kennedy R E and Thomas N E 2013 Regional dynamics of forest canopy change and underlying causal processes in the contiguous US J. Geophys. Res. Biogeosci. 118 1035–53

[59] Chambers J Q, Negron-Juarez R I, Marra D M, Di Vittorio A, Tews J, Roberts D, Ribeiro G H P M, Trumbore S and Higuchi N 2013 The steady-state mosaic of disturbance and succession across an old-growth central amazon forest landscape Proc. Natl Acad. Sci. 110 3949–54