Review

Global satellite monitoring of climate-induced vegetation disturbances

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Terrestrial disturbances are accelerating globally, but their full impact is not quantified because we lack an adequate monitoring system. Remote sensing offers a means to quantify the frequency and extent of disturbances globally. Here, we review the current application of remote sensing to this problem and offer a framework for more systematic analysis in the future. We recommend that any proposed monitoring system should not only detect disturbances, but also be able to: identify the proximate cause(s); integrate a range of spatial scales; and, ideally, incorporate process models to explain the observed patterns and predicted trends in the future. Significant remaining challenges are tied to the ecology of disturbances. To meet these challenges, more effort is required to incorporate ecological principles and understanding into the assessments of disturbance worldwide.

Global disturbance detection

Changing climate has been linked to an increased rate of vegetation disturbances and mortality, promoting major changes in the condition of forest and woodland ecosystems [1–5]. These disturbance events have been observed across all biomes and plant functional types on all vegetated continents [6,7]. These findings have led to the development of a hypothesis that climate warming is associated with increased physiological stress that is causing elevated mortality of tree and woodland species globally [6,7]. In addition to the well-demonstrated links to disturbance changes on the carbon cycle [8–11], disturbed ecosystems also have impacts on human society (e.g., [12]).

Management options for mitigating and adapting to disturbances are easier *a priori* rather than *a posteriori* [13], but we must first understand when, where, why, and at what scale these disturbances occur. To date, there is no consistent map of past disturbance events and their causes at the global scale. Multidecadal observations of disturbance events and their associated mortality are limited to sparse plot studies; thus, we cannot test the hypothesis that disturbance events are increasing in size and number [6,7]. It is even more challenging to document disturbance causes and impacts.

Disturbance information is also needed to constrain and evaluate dynamic global vegetation models (DGVMs). Disturbance processes are incorporated into DGVMs as simple approximations (e.g., [14–17]). Among the greatest limitations to disturbance simulation is the paucity of global

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disturbance data to inform and evaluate the models [18]. It is critical that we provide this information so that DGVMs, which are essential components of both impacts and climate prediction within earth system models, can be improved to capture disturbance processes.

Remote-sensing data volumes and computational methods have recently led to rapid advances in capability that promise to substantially improve understanding of disturbances. We argue in this review that such advances be accompanied by improved integration with ecological understanding, modeling, and direct observations. To this end, we propose an idealized framework (Figure 1A) for a global disturbance detection and attribution system for hypotheses testing across a range of disturbance types and scales (Figure 1B). We review the state of remote sensing of vegetation disturbances, highlight the challenges that remain, and examine the evidence supporting our proposed global disturbance monitoring system. We present both original and published data to support our analytic framework. A dominant property of this review is that ecological understanding of disturbance and succession processes has a critical role in the interpretation of remotely sensed imagery of disturbance.

Defining and observing disturbance

No single definition of disturbance satisfies all scientific and societal questions; thus, our definition must be explicit

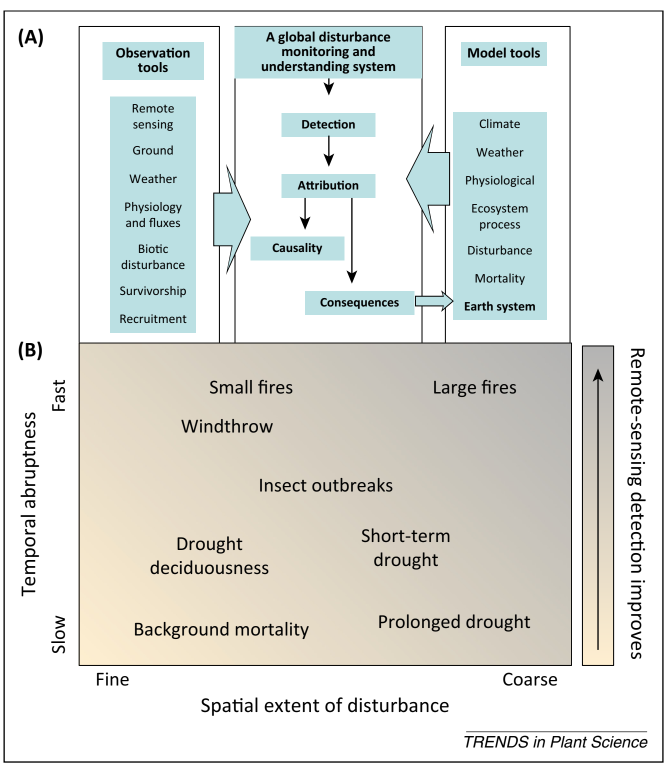

Figure 1. A global disturbance-monitoring framework. **(A)** Our proposed global disturbance monitoring and understanding framework includes not only remote sensing as the critical observational tool, but also multiple other observational and modeling tools to understand attribution, causation, and consequences. The tools refer specifically to the scale and process of interest; for example, ground tools for assessing disturbance, meteorological stations to assess weather, and so on **(B)** Quantifying terrestrial disturbances with remotely sensed imagery is inherently dependent on the spatial resolution of the images and frequency of data collection relative to the extent of the disturbances and the speed of disturbance occurrence and recovery.

and simple. For the purposes of defining the working requirements of a globally comprehensive disturbance monitoring system, we propose that disturbances are any processes that lead to the significant removal of canopy leaf area and live biomass. By this definition, mortality of entire individuals (see [18] for mortality definitions) is not required for a disturbance; rather, only dieback of the canopy at an anomalous rate compared with slower and smaller dieback associated with competition and interannual climate variability [19].

Disturbance events occur at a range of spatial and temporal scales and include wind (including hurricanes), fire, drought, floods, insects and pathogens, harvest, ice, hail, avalanches, and landslides (and harvests; which is not a focus of this review). These can occur instantaneously or over years. Disturbance detection is often based on changes in foliage, because this is the most vulnerable biotic component of terrestrial ecosystems observable from optical observations [20–22]. Although we have a wealth of knowledge, we still do not have sufficient understanding of disturbances to forecast their occurrence and impacts under changing climate conditions [23,24].

An example of the challenges and potential of remotely sensed disturbances

Remote sensing has been used for detection of disturbance since satellite-based optical technologies first became available [25]. The combination of a range of spatial and temporal signatures of disturbance, coupled with the range of spatial and temporal detection capability of the various satellite-based instruments, leads to a range of trade-offs that must be balanced to maximize detection accuracy. Among many disturbance indices, the Moderate Resolution Imaging Spectrometer (MODIS) Global Disturbance Index (MGDI), using information on vegetation greenness and surface temperature, allows global monitoring of disturbances at an annual time-step (e.g., [26,27]; Figure 2A). MGDI is principally designed for global coverage with low spatial resolution and a limited temporal history (500 m from 2005 to 2012 in Figure 2A), which is generally too coarse for monitoring localized disturbances [28].

Imagery at finer spatial scales (optical: 30–80 m; thermal: 60–120 m) has been available since the launch of Landsat-1 in 1972 [25] and allows for more detailed analysis of disturbances. Historically, high costs and limited computing power resulted in a single-scene analysis strategy; however, recent changes resulting in an open and free data access policy have greatly increased the amount of Landsat imagery being analyzed. This resulted in the first global assessment of forest-cover change at a 30-m spatial resolution from 2000 to 2012 ([29]; Figure 2B), utilizing new processing methods and interface development in a cloud computer platform.

Differences between the 500-m (MGDI) and 30-m resolution maps (contrast Figure 2A and 2B) are a function of application domain, temporal frequency, and spatial resolution. For example, the algorithms differ in their use of vegetation and biophysical indices. Furthermore, the 500-m coarse resolution of MODIS misses disturbances occurring at the finer scales [30]; however, MGDI classifies