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Towards a unifying framework of disturbance ecology through crowdsourced science

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Abstract. Disturbances fundamentally alter ecosystem functions; yet predicting the impacts of disturbances remains a key scientific challenge. The study of disturbances is ubiquitous across almost all ecological disciplines, yet varying terminology and methodologies have led to the lack of an agreed upon, cross-disciplinary foundation for discussing and quantifying the complexity of disturbances. This shortcoming presents an increasingly urgent challenge due to accelerating global change and the threat of interacting disturbances that can further destabilize ecosystem responses. By harvesting the 'swarm intelligence' of an interdisciplinary cohort of contributors spanning 42 institutions across 15 countries, we propose a pathway towards a new conceptual model of ecological disturbances. Together we identify an essential limitation in disturbance ecology—that the word 'disturbance' is used interchangeably to refer to both the events that cause and the consequences of ecological change, despite fundamental distinctions between the two meanings. We develop a generalized framework of ecosystem disturbances to reconcile this limitation and enable examination of the drivers and impacts of disturbances simultaneously. Our proposed framework puts forth a well-defined lexicon for understanding disturbance across perspectives and scales, thereby increasing the interoperability of research across scientific domains. We also recommend minimum reporting standards that detail the magnitude, duration, and rate of change of driver and response variables, regardless of scale. Importantly, while we address some challenges of disturbance research here, developments in technology, methodology, and cross-disciplinary approaches are necessary to close knowledge gaps. We therefore propose four future directions to advance our interdisciplinary understanding of disturbances and their social-ecological impacts: integrating across ecological scales, understanding disturbance interactions, establishing baselines and trajectories, and developing process-based models and ecological forecasting initiatives. Our experience through this process

motivates us to encourage the wider scientific community to continue to explore new approaches for leveraging Open Science principles in generating creative and multidisciplinary ideas.

Introduction.

Disturbances, including those related to human activities and changing climate, are predicted to continually increase in frequency and severity in the coming century. For instance, wildfires have ravaged global landscapes over the last two decades, impacting human lives, crops, and biodiversity — highlighted by recent outbreaks in Australia, Brazil, California, and British Columbia (Cleetus & Mulik, 2014; Tedim et al., 2020). Twenty of the hottest years in history have occurred in the past 22 years (WMO, 2018), and extreme events like marine heat waves are projected to increase in frequency by more than an order of magnitude as climate change continues (IPCC, 2019). Such disturbances can radically alter trajectories of ecosystem processes, and importantly, they occur within a broader ecological context that can generate disturbance interactions and lead to unpredictable ecosystem responses (Brando et al., 2019; Calderón et al., 2018; Carlson, Sibold, Assal, & Negron, 2017; Knelman, Schmidt, Garayburu-Caruso, Kumar, & Graham, 2019; Mehran et al., 2017; Pidgen & Mallik, 2013; Ryo, Aguilar-Trigueros, Pinek, Muller, & Rillig, 2019; Zscheischler et al., 2018).

Despite increases in the frequency and severity of disturbance events, predicting their onset, characteristics, and consequences remains difficult in part because of differences in conceptual models, scales of investigation, and language used across scientific disciplines. Inconsistencies in disturbance frameworks have long been noted by the ecological community (Pickett, Kolasa, Armesto, & Collins, 1989; Poff, 1992; Rykiel Jr., 1985), and the struggle to derive a common framework for understanding and predicting disturbances continues in modern literature (Borics, Várbíró, & Padisák, 2013; Buma, 2015; Hobday et al., 2016; Jentsch & White, 2019; Smith, 2011b). Terms such as disturbance, pulse event, perturbation, threat, and stressor are often not clearly defined or used interchangeably, but have subtle and meaningful differences in specific fields of inquiry (Borics et al., 2013; Jentsch & White, 2019; Keeley & Pausas, 2019; Kemppinen, Niittynen, Aalto, le Roux, & Luoto, 2019; Lake, 2000; Rykiel Jr., 1985). For instance, Slette et al. (2019) revealed that the plethora of literature on drought is generally based on loose descriptions rather than explicit definitions or quantitative metrics of drought, while Hobday et al. (2018) noted that other disturbances lack even basic quantitative categorization or naming schemes. Because of these inconsistencies, attempts to compare disturbances across types and ecosystems have resulted in few outcomes that can be generalized across fields (Peters et al., 2011). Collectively, these shortcomings point to the need for an interdisciplinary understanding of disturbances.

Differences in how disturbances are studied are driven in part by their spatial and temporal heterogeneity and by differences in typical scales of investigation across scientific disciplines. Indeed, disturbances occur through space and time with different frequencies (number of occurrences per unit time), intensities (magnitude of the disturbance), and extents (spatiotemporal domain affected)(Grimm & Wissel, 1997; Miller, Roxburgh, & Shea, 2011; Paine, Tegner, & Johnson, 1998). While some disturbance events have relatively discrete temporal and spatial boundaries (e.g., wildfires, hurricanes, earthquakes), others are diffuse or overlap in time and space (e.g., ocean acidification, overgrazing, nutrient loadings)(Godfrey & Peterson, 2017). This makes it difficult to identify which events depart from ‘normal’ conditions, especially within the broader context of ongoing environmental change (Duncan, McComb, & Johnson, 2010; Mishra & Singh, 2010; Slette et al., 2019). Finally, because disturbances are contingent on historical events and local social-economic conditions (Dietze et al., 2018; Duncan et al., 2010; Seidl, Spies, Peterson, Stephens, & Hicke, 2016; Słowiński et al., 2019), a single type of event can have many different outcomes. Dynamic hydrology, for example, is fundamental to floodplain wetland systems, which are adapted and shaped by flooding events, but flooding events are typically considered disturbances in upland contexts.

We therefore need generalizable theory to predict the frequency and significance of disturbance events, and to more sustainably manage our planet's ecosystems in ethical and efficient ways. Ideally, this framework would be able to manage the heterogeneity inherent in disturbances while providing consistency in how disturbances are defined and studied. Such a foundation would consist of shared goals and be built upon commonly agreed upon terms and metrics. To address this challenge, we used an open call on social media to assemble a cross-disciplinary team of 50 collaborators across 42 institutions in 15 countries with a diverse suite of scientific specialties (Graham & Krause, 2020). We used our collective 'swarm intelligence' to propose a pathway towards a new conceptual model of ecological disturbances that integrates contributions across disparate disciplines. The project featured a flexible, collaborative, and iterative writing process (using Google docs), freely open authorship opportunities advertised via Twitter, and was coordinated by a small international leadership team. By proposing a unifying framework for disturbances, we strive towards a common currency to compare ecological drivers and responses under many conditions and in many systems.

We present this paper in five main sections. First, we provide an overview of the theoretical ideas used across disciplines to study disturbances in 'System Stability as a Common

Foundation.' Then, we highlight 'Spatiotemporal Considerations' as major challenges to and key aspects of developing a unifying framework. The final three sections describe: i) a unifying framework derived from crowdsourced scientific knowledge, ii) minimum reporting standards for widely implementing this framework, and iii) cross-disciplinary approaches for addressing areas of need. This emergent framework is intended to facilitate outcomes such as increased potential for synthesis among historically disparate events and disciplines, more rigorous tracking of events across space and time, and new ways of understanding disturbance impacts between fields. In turn, resulting knowledge can influence the ways in which humans manage ecosystems and their responses to disturbances by aiding managers in identifying slow-developing disturbances as they occur, referencing disturbances against historical events by comparing quantitative characteristics, and being able to better predict ecological impacts.

System Stability as a Common Foundation.

System stability has been a pillar of disturbance research across scientific domains (Duncan et al., 2010; Hodgson, McDonald, & Hosken, 2015; Ives & Carpenter, 2007; Seidl et al., 2016; Todman et al., 2016). Because many areas of research rely on stability concepts to describe a system's response to environmental change, it is integral for a cohesive understanding of disturbances. For example, using this common theoretical foundation, biodiversity has been repeatedly linked to the capacity of ecosystems to be resistant to biological invasions (Cardinale et al., 2012; Cardinale & Palmer, 2002; Isbell, Polley, & Wilsey, 2009; Kardol, Fanin, & Wardle, 2018); and managed ecosystems rely on this theory to maintain a stable system with socially-desirable flow of timber and food (Foley et al., 2005; Folke, 2002; Peterson, Collavo, Ovejero, Shivrain, & Walsh, 2018; Rist et al., 2014). At the other end of the spectrum of biological sciences, human geneticists have applied system stability theory to demonstrate that context-specific gene expression buffers systems from changing ambient conditions (Ghavi-Helm et al., 2019). Here, we review core and emerging system stability theory to form a conceptual basis for an interdisciplinary approach to understanding disturbance discussed in later sections.

There are several aspects of system stability theory that are common throughout social-ecological domains, including the concepts of resilience, resistance, and redundancy. Resilience is commonly defined as the ability of a system to recover from disturbance, while resistance is the ability of an ecosystem to remain unchanged when being subjected to disturbance (Griffiths & Philippot, 2013; Gunderson, Holling, Pritchard, & Peterson, 2002; Crawford S Holling, 1973; Crawford Stanley Holling, 1996; Lamentowicz et al., 2019; McCann, 2000; Seidl et al., 2016; Westman, 1978). Resistance and resilience are quantified using various metrics, including the time, slope/rate, and angle of recovery relative to a baseline state (J. H. Connell & Sousa, 1983; Shade et al., 2012). Additionally, functional redundancy and the 'insurance hypothesis' (Yachi & Loreau, 1999) are also used throughout ecology to describe the capacity of a system to resist and recover from a disturbance whereby the presence of functionally redundant phenotypes enhances ecosystem stability (Naeem & Li, 1997; Yachi & Loreau, 1999). Recent frameworks built on these foundations have emerged to provide a more holistic and ecologically relevant concept of system stability by employing multidimensional concepts of system stability (e.g., temporal variability)(Hillebrand et al., 2018).

Another central paradigm in stability theory is that the intensity of disturbance response is often non-linearly related to the intensity of the disturbance itself. There is a growing understanding of the importance of tipping points that, when reached or exceeded, cause strongly non-linear system responses and potential sudden shifts in system behavior (Dai, Vorselen, Korolev, & Gore, 2012; Loecke et al., 2017). For instance, work by Scheffer et al. (2001) has shown that ecosystems can deviate rapidly from their current state due to minor shifts in underlying biotic or abiotic drivers. Similarly, slow and often undetectable changes can reduce ecosystem resilience, leading to unpredictable system collapses (B. H. Walker, Carpenter, Rockstrom, Crépin, & Peterson, 2012). When pressures exceed ecosystem tipping points, regime shifts can occur and ecosystems are pushed into a different (alternative) state that is maintained by self-reinforcing feedbacks (Pausas & Bond, 2020). While there is growing capacity to predict regime shifts (e.g., by rising variance in ecosystem properties or by slow recovery rates), several challenges remain in their prediction, in part due to the challenge of measuring appropriate indicators for resilience (Dai, Korolev, & Gore, 2013; Dai et al., 2012; Munson, Reed, Peñuelas, McDowell, & Sala, 2018; Scheffer, 2010; Scheffer et al., 2009; Van Nes & Scheffer, 2007). Collectively, historical and emerging research on system stability provides a common foundation for understanding disturbances across a broad suite of ecosystems and across lines of investigation with different underlying objectives.

Spatiotemporal Considerations.

Though the specific nature of disturbance extent and duration can vary greatly, all disturbances occur over space and time; any unifying framework must therefore consider the spatiotemporal extent and variability of disturbance properties. This includes a critical need to define the baseline conditions relative to which a disturbance is assessed in order to build a set of domain-agnostic principles. These baselines may vary as a function of the spatiotemporal scale over which an analysis is being performed, and the deviation a system undergoes from its baseline at a given scale can be used to assess a disturbance's intensity and impact (e Silva, Semenov, Schmitt, van Elsas, & Salles, 2013). However, as ecosystems change in response to climate, land-use change, and other human impacts, conditions which were once considered disturbed against a static baseline may now shift into a new normal range of variation (Figure 1). In this section, we review key spatial and temporal perspectives that influence disturbances and that should underlie an interdisciplinary understanding of disturbance.

Spatial Perspectives on Disturbance Events

The drivers and impacts of disturbance are dependent on the spatial features of their broader landscapes and the spatial perspective of a given study's objectives. For example, pre-existing ecosystem characteristics, such as habitat connectivity and topography, influence the spatial structure of disturbance impacts by dictating its ability to spread as well as the ecosystem's ability to be recolonized by surviving organisms in neighboring spaces (Buma, 2015; Drever, Peterson, Messier, Bergeron, & Flannigan, 2006; Turner, Romme, & Gardner, 1994). Further, the spatial perspective taken when studying a disturbance can also heavily influence conclusions drawn about its effects. Spatial perspectives and extents can vary tremendously, and are defined by the overarching research question as well as the ecosystems and/or organisms of interest. Some disturbances, for instance fine-scale temperature shifts, may be apparent only at local scales while others impact regional and coarser scales (Aalto, Riihimäki, Meineri, Hylander, & Luoto, 2017; Lembrechts, Nijs, & Lenoir, 2019). In general, disturbances that directly affect species interactions tend to be observable at local scales (Mod, le Roux, & Luoto, 2014), while disturbances related to habitat alterations are detectable at coarser spatial resolution (Chase, 2014; Dumbrell et al., 2008; Hamer & Hill, 2000; Hill & Hamer, 2004).

Additionally, because separate factors control ecosystem dynamics at different spatial scales, the impacts of, and ecosystem responses to, disturbances depend on how various disturbances modify scale-specific controls on ecosystems (e.g. species interactions influence communities at local scales vs. climate at larger scales)(Cohen et al., 2016; Dobson, Rodriguez, Roberts, & Wilcove, 1997; Dumbrell et al., 2008; Wei & Zhang, 2010). For example, extant dispersal rates and disturbance scale can regulate the recovery of disturbed ecological communities and the spread of impacts across space to neighboring populations (Zelnik, Arnoldi, & Loreau, 2019). Furthermore, spatial extent and patterning of disturbances can influence disturbance impacts. Although disturbances that homogenize landscapes or reset successional trajectories such as volcanic eruptions and glaciation events have been a core interest in ecological studies, less well-studied moderate disturbances that do not decimate landscapes tend to increase system heterogeneity, with entirely different functional consequences for ecosystems and resultant landscape-scale spatial patterns (Curtis & Gough, 2018; Hardiman, Bohrer, Gough, Vogel, & Curtis, 2011; Knelman, Graham, Trahan, Schmidt, & Nemergut, 2015; Lorimer, 1989; Luyssaert et al., 2008; Ruhi, Dong, McDaniel, Batzer, & Sabo, 2018; Turner, 2010; Turner et al., 1994). Therefore, an interdisciplinary approach to understanding disturbance must consider both the spatial properties of disturbances themselves as well as the spatial scale-dependence of their effects.

Temporal Perspectives on Disturbance Events

For a common understanding of disturbances, we also need to acknowledge the central influence of time without explicitly defining a single general time scale of disturbances; with the longest potential timespan starting with the evolution of life and the shortest bounded by the finest temporal grain at which any attribute of interest can be measured (Ladau & Eloe-Fadrosh, 2019). Some disturbances impact ecosystem dynamics over short time scales (i.e., pulse events), whereas other disturbances operate over long time periods (i.e., ramp and press events)(J. Connell, 1997; J. H. Connell, Hughes, & Wallace, 1997; Jentsch & White, 2019). A single type of event may constitute a disturbance at one timescale, but not at another. While a forest fire may be a significant deviation from an environmental baseline considered on annual or decadal scale (and therefore, a disturbance at this timescale), it may fall within the historical range of environmental variation at a centennial timescale (and therefore, not a disturbance at this timescale). Furthermore, the effects of slow increases in mean annual temperatures may be insignificant over the course of a few years when considering the background variation in mean annual temperatures (IPCC, 2018). However, at a centennial scale, the warming trend shifts the mean as well as the extreme temperatures generating climates outside the range of historical variation. Similar arguments can be made for nitrogen deposition, chronic fertilization, pesticide applications, elevated CO_2, and many other global disturbances (Ferretti, Worm, Britten, Heithaus, & Lotze, 2010; Jackson et al., 2001; Ripple et al., 2014).

This temporal perspective highlights that changing conditions through time ('non-stationarity' (Wolkovich, Cook, McLauchlan, & Davies, 2014)) is also a central consideration for any conceptualization of disturbances to be applicable in the future. Baseline conditions and driver–response relationships are dynamically conditioned by the legacies of disturbance and ecological memory (Johnstone et al., 2016; Nowicki et al., 2019). Ecological succession is a classic example of ecosystem trajectories that interacts with more discrete events to yield an aggregate disturbance impact. Disturbances can interrupt and potentially alter trajectories of succession through impacts on community dynamics that dramatically alter ecosystem functions (Ghoul & Mitri, 2016). For example, antibiotic administration and delivery mode can disrupt microbial community assembly and succession in the human infant gut microbiome that in turn can drive long-term impacts on host health (Koenig et al., 2011). Over longer timescales, the field of paleoecology can describe pre-anthropogenic conditions to define the long-term baseline state preceding a disturbance, but paleoecology is rarely integrated with other disciplines (Bartowitz, Higuera, Shuman, McLauchlan, & Hudiburg, 2019; Lamentowicz et al., 2019; Ryo et al., 2019; Słowiński et al., 2019).

Rising Importance of Interacting Disturbances

An obstacle to historical paradigms of disturbance theory is that changes in environmental conditions will not only alter the frequency of disturbances, but also the potential for multiple interacting disturbances to impact system stability (Seidl et al., 2017). Multiple interacting disturbances can lead to novel ecosystem responses, compromising our abilities to understand disturbances in unknown future environments (Brando et al., 2019; Calderón et al., 2018; Carlson et al., 2017; Hobbs et al., 2014; Hobbs, Higgs, & Harris, 2009; Knelman et al., 2019; Mehran et al., 2017; Pidgen & Mallik, 2013; Ryo et al., 2019; Zscheischler et al., 2018). Two or more disturbances can have a multiplicative effect on an ecosystem, sometimes impacting an ecosystem's resilience to the second disturbance (Buma, 2015; Darling & Côté, 2008; Folt, Chen, Moore, & Burnaford, 1999). For instance, climate change-related disturbance can combine with species interactions to alter the impact and outcomes of disturbances (Arora et al., 2019; Mod & Luoto, 2016; Myers-Smith et al., 2011; Niittynen, Heikkinen, & Luoto, 2018; Zarnetske, Skelly, & Urban, 2012). Additionally, impacts at multiple spatial scales can also interact. Local disturbances can play an important role in maintaining regional biodiversity through patch dynamics mediated by species traits (e.g., competition-colonization trade-offs)(He, Lamont, & Pausas, 2019; le Roux, Virtanen, & Luoto, 2013; Tilman & Downing, 1994), which may reduce vulnerability to larger scale disturbances. Local disturbances can also exacerbate impacts of more widespread regional disturbances, placing ecosystems under increased threat of collapse (Kendrick et al., 2019). If resilience is overcome because of multiple disturbances, then compound disturbances may cause a state change or 'ecological surprise' that is largely unpredictable (Paine et al., 1998).

Given the variation that occurs both in disturbed systems and in the goals of disturbance studies and applications, we present a framework that describes a minimum foundation for best practices for creating and sharing knowledge about disturbed systems in a novel and changing world.

A unifying framework.

Because of the spatial, temporal, and cross-disciplinary complexities in studying disturbances, disturbance theory lacks a one-size-fits-all approach. A key challenge in the development of such an approach is that individual disturbances operate within a broader context of historical events that cumulatively alter disturbance magnitude and impact. For instance, Ryo et al. (2019) describe the temporal dependency of interacting disturbances in terms of 'nestedness', wherein the complexity of interactions is dependent on the relative closeness of the events. Within this framework, a single event is a subset of multiple disturbances within a continuous trajectory. Importantly, there are carryover effects within trajectories in which disturbance impacts can accumulate and/or alter the internal mechanisms affecting responses through time, even for parts of an ecosystem not affected by earlier disturbances (Nowicki et al., 2019). Therefore, driver-response relations are dependent on both short- and long-term histories. While Ryo's framework only considers temporal aspects of disturbances (Ryo et al., 2019), it highlights the need for a fluid framework to provide a common foundation for studying disturbances across scales and lines of inquiry—one that can adjust for variation between systems and research goals.

One essential limitation in our understanding and managing of disturbances is that the word 'disturbance' is used interchangeably to describe two distinct processes—events that cause ecological change and consequences of extreme events—that are both termed disturbances despite fundamental distinctions between the two types of processes. Some researchers define disturbances by properties that describe an event (e.g., type, frequency, intensity)(Hobday et al., 2016; Hobday et al., 2018), while others define disturbances by their impacts (e.g., ecological or societal damages)(Smith, 2011a). Furthermore, many definitions of disturbances solely consider short-term events that represent rapid deviations from a biotic or abiotic background state without regard to historical processes (Jentsch & White, 2019). Finally, solely defining disturbances by their impact size directly conflicts with the idea of ecological resistance and the vast amount of theory developed for this phenomenon. If we were to define a disturbance based only on its impact, highly resistant ecosystems would never be disturbed regardless of the prevalence of extreme events.

By parsing disturbance theory between the causes and consequences of a disturbance, we propose a robust and tangible framework of disturbance that is applicable regardless of the line of inquiry and/or spatiotemporal scale of investigation (Figure 2). Specifically, we define a *disturbance driver* as an event whereby a force, either biotic or abiotic, generates a deviation from the local, prevailing background conditions. In the proposed framework, a driver is characterized by its magnitude of deviation from an environmental baseline (low to high deviation describes weak to strong drivers). In contrast, a *disturbance impact* represents the social-ecological consequences of a driver relative to a scale-dependent baseline state. Impacts can be positive or negative depending on the perspective of the study. Using relationships between disturbance drivers and disturbance impacts, we generate *four universal definitions of disturbances* with variation within each type due to the strength of the driver and the size of the impact. We conceptualize disturbance drivers, either abiotic or biotic, on an x-axis and the impact of disturbance impacts on a y-axis. This yields four quadrants: weak driver-positive impact, strong driver-positive impact, weak driver-negative impact, and strong driver-negative impact. The position of drivers and impacts across and within the quadrants slides with the line of inquiry (Figure 2, examples in the following paragraph).

A single driver may yield a different impact depending on its impact relative to the scale and/or scope of the investigation. For example, when viewed from the perspective of a drought-sensitive microorganism, a 10-day drought is a severe disturbance whereas it could be inconsequential for humans in urban environments (Figure 2). Two floods in rapid succession in a single area may have disparate social-ecological outcomes dependent on the impacts of the first event. Additionally, the disturbance impact for a single driver could be simultaneously positive and negative, dependent on scale. For example, deforestation for agriculture could be positive from an immediate human perspective (food production) but negative from an ecological perspective (habitat loss). This allows for interacting and compounding disturbances to be viewed within the same framework as single events and for events that cause tipping points to be represented as weak driver-high impact events. Spatial and temporal scales are also implicitly represented in the proposed framework, as historical exposures have direct effects on the impact of a given driver and the scale of interest defines the magnitude of both the driver and impact. Likewise, the ecological state of a system (e.g., its stability, resistance, resilience, and successional stage) also influences the ‘impact’ axis of disturbances through escalating or mediating the impact. Definitions and examples of each quadrant are presented in more detail in Table 1 and Figure 2.

The advantage of conceptualizing and classifying disturbances into this inclusive framework is to increase interoperability of disturbance research across scientific domains. While the current framework is qualitative in nature and based upon discipline-specific expert knowledge of driver and impact magnitudes, there are further opportunities to develop quantitative thresholds to separate quadrants for particular lines of investigation. For example, a disturbance driver and impact size falls within a range of historical variation that is specific to the event type. Quantitative thresholds for event types can then be developed to separate events along driver and impact axes based on the distribution of historical events along those axes. Towards this end, it then becomes necessary to follow standardized reporting practices to characterize the historical range of variation of disturbances and to classify individual events within a scale-flexible framework. In the next section, we propose a set of minimum reporting standards to facilitate comparability between distinct disturbance investigations.

Minimum reporting standards.

Because scales of investigation vary tremendously between disciplines, it is necessary to present sufficient data in publications and community repositories that capture complexity for other researchers to evaluate the placement within this framework. When possible, standardized indices are suggested to explicitly describe disturbances (e.g., Palmer Drought Severity Index, Standardized Precipitation Evapotranspiration Index)(Palmer, 1965; Slette et al., 2019). In ecological research, indices are most well-described for plot-scale studies and anthropocentric framings of scale that relate to our own human experiences rather than ecological processes (e.g., monetary losses from hurricanes), while they are more nascent for cross-scale disturbance work. Therefore, in addition to indices, it is necessary to report variables that describe the magnitude, duration, and rate of change of drivers and response variables in a consistent manner that is applicable regardless of scale.

We suggest three categories of variables for minimum reporting standards: (1) ecosystem properties, (2) driver descriptors, and (3) impact descriptors with suggested variables for each listed in Table 2. An integral distinction of these standards compared to previous efforts is the explicit recording of spatial and temporal scales needed for interoperable understanding of disturbances (Peters et al., 2011). Ecosystem properties are foundational variables that provide context for disturbance interpretation (e.g., ecosystem type, successional state, and system stability). Driver and impact descriptors are each divided into three categories: reference, spatial, and temporal variables. These variables capture system stability and spatiotemporal dynamics that allow for multiscale comparisons including mild versus extreme intensity, acute versus chronic timescales, and abrupt versus gradual change (Ryo et al., 2019). Collectively, they allow for the placement of events on both the driver and impact axes of the proposed conceptual framework as well as providing context that describes the scale and scope of the investigation.

Promising Cross-Disciplinary Approaches to Address Areas of Need.

While we address some challenges of disturbance research here, developments in technology, methodology, and cross-disciplinary approaches are necessary to close knowledge gaps. Questions such as “How do we define a disturbance in the context of a non-stationary baseline?” and “When does a disturbance begin and end?” are difficult to address with current state-of-science approaches. For the study of disturbance, there simply may not be a suitable universal approach. Below, we propose areas of promise for advancing an interdisciplinary understanding of disturbance.

In particular, we highlight the need to *integrate disturbance responses across scales of ecological organization* from genes to ecosystems. We expect that future studies have the opportunity to consider multiple scales of sampling and analysis that comprehensively evaluate disturbances and their effects across spatial, temporal, and/or organismal scales. Ecological hierarchies, in particular, underlie self-organized ecosystems and provide a structure for using information theory and other advanced statistical techniques to predict whole ecosystem impacts (Allen & Starr, 2017; Arora et al., 2019; Cumming, 2016). Social-ecological applications of machine learning, graph theory, and information theory are exponentially increasing and can decipher complex relationships in multidimensional data streams. These approaches are used to collapse complex data types into tangible variables by deciphering classes of organisms and relationships among these classes through space or time. They reveal the organizational structure of a system through interaction networks that include both random and ordered processes (Ings et al., 2009). Remote sensing can also aid in evaluating the spatial extent and spatial patterning of disturbance, thereby defining the appropriate scale of sampling for these analyses (Shiklomanov et al., 2019). However, empirical tests on the potential for disturbance impacts to propagate through ecosystem hierarchies are lacking and is a major research need. One opportunity would be the use of paired experimental and modeling approaches to elucidate networked changes in ecological systems resulting from disturbance impacts. The use of experiments and clearly outlined hypotheses is increasingly argued as a core need for generating predictive understandings of ecosystem responses to disturbance (Currie, 2019; Spake et al., 2017).

Our second area of need also considers the broader issue of scale—understanding *how disturbances interact with each other* and potentially compound through space and time. Recent work has underscored interactions between extreme events occurring closely in space and time, for example by elucidating discrete effects of flooding on biogeochemistry depending on prior fire exposure (Knelman et al., 2019). Long-term processes such as environmental change also have multifaceted impacts on ecosystems but are most frequently studied independently (Rillig et al., 2019; Song et al., 2019). Such work raises new questions into ecosystem trajectories—as disturbances increase through time, are there thresholds beyond which ecosystems are irreversibly altered? The evolutionary consequences of living in an environment with recurrent disturbances are also poorly understood (Pausas & Keeley, 2014; Pausas, Keeley, & Schwilk, 2017). Some species, for example, have evolved specific life-history adaptations that enable them to not only survive and exploit disturbances, but even to require them for their persistence (e.g., alpine vegetation, riparian cottonwoods)(le Roux et al., 2013; Lytle & Poff, 2004; Mahoney & Rood, 1998). Similarly, disturbances have countervailing effects on population dynamics in that they can cause immediate mortality of species, but also create new habitat, thereby increasing growth rate or increasing population size post-disturbance (McMullen, De Leenheer, Tonkin, & Lytle, 2017; Pausas & Keeley, 2014). For instance, if the consequences of climate change related disturbances are studied separately, the results may be greatly biased as compared to when the consequences are considered simultaneously (Niittynen et al., 2018). Therefore, the interactions between disturbances that change eco-evolutionary dynamics provide a relatively unexplored area for future research.

A third research need, *establishing appropriate baselines and trajectories* for different ecosystems, disturbance, and organism types, is essential for evaluating disturbances that alter ecosystem structure and function. Paleoecological data can provide historical reference baselines, help evaluate sensitivity to disturbances across different windows of space and time, and unveil past state changes that provide a foundation for understanding how ecological hierarchies will respond to future environmental changes (Lamentowicz et al., 2019). Time series methods are also well-equipped to separate disturbances from long-term trends and evaluate changes in disturbance regimes through time (e.g. wavelet analysis)(Keitt, 2008; Tonkin, Bogan, Bonada, Rios-Touma, & Lytle, 2017). For instance, Sabo and Post (2008) developed tools based on Fourier analysis to disentangle the periodic (seasonal), stochastic (interannual), and catastrophic components of river flow regimes. Space-for-time approaches, in which distances from an event are used as a proxy for the time-since-event, can reveal long-term impacts without necessitating decades of monitoring (Pickett et al., 1989; L. R. Walker, Wardle, Bardgett, & Clarkson, 2010). Although space-for-time investigations require a correlation between the age of an ecosystem attribute and spatial structuring that may not be applicable to highly disturbed landscapes, chronosequences can be used to investigate plant and soil successional processes at decadal to millennial scales (Laliberté et al., 2013; Sutherland, Bennett, & Gergel, 2016; L. R. Walker et al., 2010; Zemunik, Turner, Lambers, & Laliberté, 2015).

Finally, we underline the need for enhancing predictive capabilities through *process-based models and ecological forecasting initiatives* that represent the drivers of disturbance impacts on ecosystem attributes, going beyond historical correlations that fail to represent causal relationships (Dietze et al., 2018; Tonkin et al., 2019). Generating a model robust to disturbance type, ecosystem, and scale that allows managers to detect disturbance drivers and predict disturbance impact sizes is one of the ultimate goals of disturbance ecology. Mechanistic models can further progress towards this goal by representing interactions among species through time

(Tonkin, Merritt, Olden, Reynolds, & Lytle, 2018). Microbial communities are useful empirical tools for developing process-based models due to their short generation times and the ability to rigorously test species-based interactions under controlled conditions (Friedman, Higgins, & Gore, 2017; Gibbons et al., 2016; Hsu et al., 2019; Venturelli et al., 2018). Furthermore, thanks to the availability of curated genome-scale metabolic models for hundreds of bacterial species, detailed metabolic interaction networks can be simulated for entire communities (Diener, Gibbons, & Resendis-Antonio, 2020; Magnúsdóttir & Thiele, 2018). Process-based and forecasting models can be tailored to highly specific conditions and can provide managers with both a predicted outcome and a range of uncertainty based on the underlying driver (Tonkin et al., 2019). They are commonly used to guide management practices in fisheries and conservation efforts (Tonkin et al., 2019). Collectively, process-based and forecasting models are potential tools developing mitigation strategies and informing how humans might intervene at individual, local, regional, and global scales to minimize social-ecological damages caused by disturbances (Berkes, Colding, & Folke, 2000; D'Amato, Bradford, Fraver, & Palik, 2011; Dale, Lugo, MacMahon, & Pickett, 1998; Folke, Hahn, Olsson, & Norberg, 2005).

Conclusion.

Using a completely open and crowdsourced scientific approach, we integrate the insights from numerous scientific perspectives to present a conceptual foundation for cross-disciplinary disturbance investigations. We highlight that the current lexicon used to discuss disturbances generates confusion by conflating events that drive ecological change with the impacts of extreme events. To overcome this challenge, we propose a unifying and tangible framework that parses disturbance theory between disturbance drivers and disturbance impacts. Using drivers and impacts as axes of variation, the framework generates four universal disturbance types that are applicable regardless of the line of inquiry or its spatiotemporal scale (Figure 2). To provide consistency in comparing disturbances within this framework, we suggest three categories of variables for minimum reporting standards: i) ecosystem properties that provide context and ii) disturbance driver and iii) disturbance impact descriptors that capture system stability and spatiotemporal dynamics.

We also highlight promising lines of research to generate a more universal understanding of disturbance events and their impacts, including integrating scales of ecological research, understanding how disturbances interact with each other, establishing appropriate baselines and trajectories, and developing process-based models and ecological forecasting initiatives that will enable robust prediction capabilities and mitigation strategies.

Our work synthesizes knowledge across global institutions from Luxembourg to Singapore using crowdsourced open science and demonstrates that novel approaches can generate emergent ideas greater than the sum of their independent disciplinary parts. The integration of interdisciplinary contributions of over 50 individuals, from 42 institutions - from academic, governmental, and non-governmental organizations - in 15 countries, into the novel conceptual framework presented here demonstrates the currently untapped potential for supporting collaborative co-creation of research, facilitated by social media and collaborative writing platforms. Our experiences through this process motivates us to encourage the wider scientific community to continue to explore the suitability of similar approaches for facilitating collaborative research that benefits from a large interdisciplinary knowledge base and allows to fully embrace Open Science principles in collaborative interdisciplinary research.

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Figures and Tables.

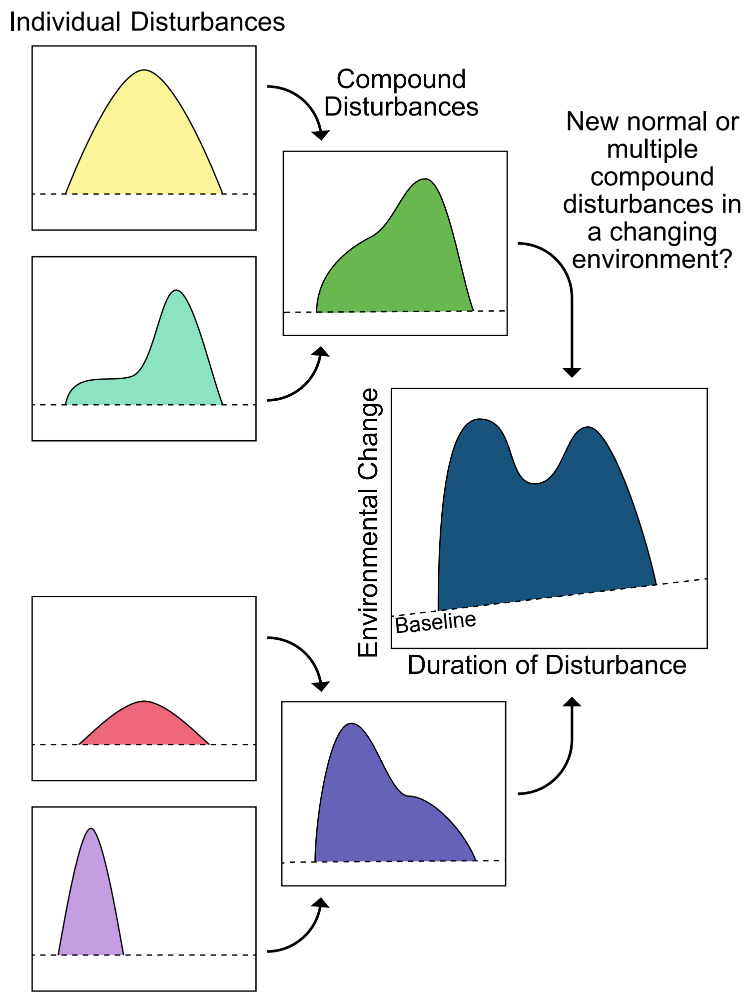

Figure 1. An obstacle to historical paradigms of disturbance theory is that changes in environmental conditions will not only alter the frequency of disturbances, but also the potential for multiple interacting disturbances. As multiple disturbances compound through time, a crucial question emerges: "When does a disturbed state become normal?" Compound disturbances can take many forms and result in both linear and non-linear ecosystem responses. As an example, Figure 1 shows an additive trajectory of disturbances and resultant environmental change. The leftmost panels represent single disturbance events that have long been the targets of scientific research. As disturbances aggregate through time, a new class of 'compound' disturbances have been a rising topic (middle panels). With the continuing increases in the frequency and intensity of disturbances, a key challenge remains to disentangle multiple compounding disturbances from normal variability in ecosystem functions (rightmost panel). Another challenge is that environmental baselines (dashed line) shift through time, adding a chronic component to the study of short-term disturbance events.

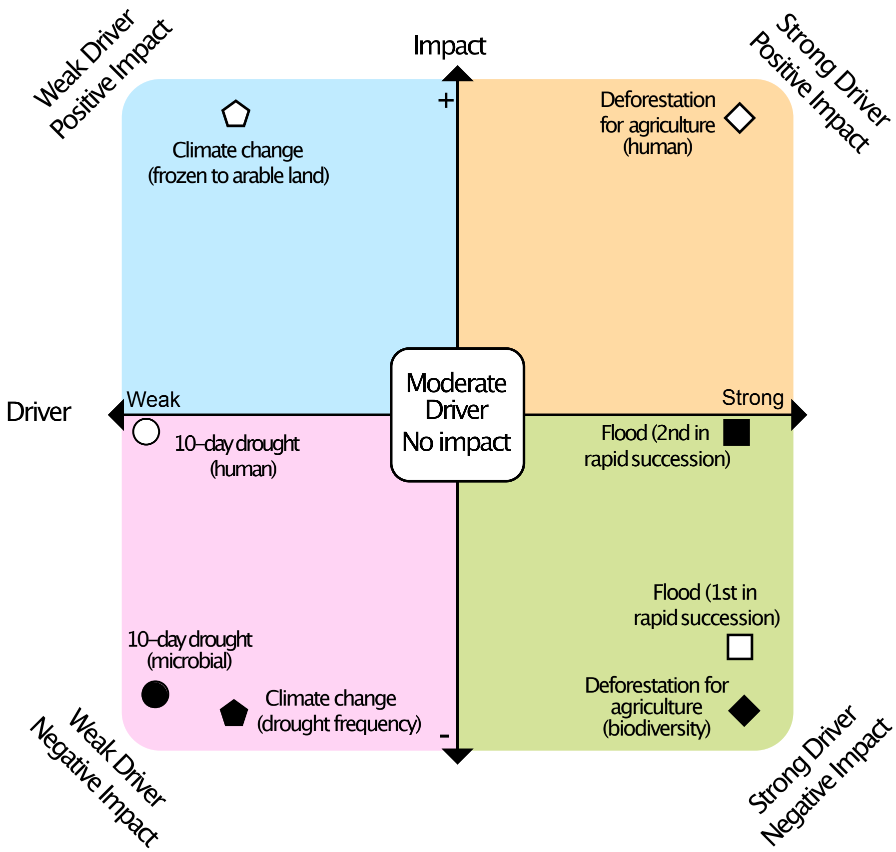

Figure 2. Current disturbance lexicon conflates two distinct processes—events that drive ecological change and impacts of extreme events—both interchangeably termed disturbances despite fundamental distinctions between the two types of processes. We disentangle these processes to derive four universal types of disturbances that are applicable regardless of the line of inquiry or its spatiotemporal scale. Drivers (x-axis) are defined as an event whereby a force, either biotic or abiotic, generates deviation from local, prevailing background conditions. A driver is characterized by its magnitude of deviation from an environmental baseline (low to high deviation denotes weak to strong driver). Impacts (y-axis) are defined as the impact of social-ecological consequences of a driver relative to a scale-dependent baseline state. Impacts can be positive or negative depending on the perspective of the study. Each quadrant is, therefore, a unique disturbance type defined in more detail in Table 1, and the position of drivers and impacts across and within the quadrants slides with the line of inquiry. Examples of disturbances across spatial and temporal scales are denoted within each quadrant.

Table 1. Description and examples of four universal disturbance types generated by proposed framework.

Quadrant	Description	Example
High Deviation-Negative Impact	Occur when large deviations from environmental baselines generate negative impacts on ecosystem functions.	Category 5 hurricane Mass wasting Oil spills Tornados Floods (human perspective) Wildfires (human perspective) Deforestation biodiversity impacts
High Deviation-Positive Impact	Occur when large deviations from environmental baselines generate positive impacts on ecosystem functions.	Deforestation for agriculture increasing crop production (human perspective) Floods (wetland ecosystems)
Low Deviation-Negative Impact	Occur when small deviations from environmental baselines generate negative impacts on ecosystem functions.	Short term drought-induced microorganism mortality Climate change-induced (i.e., temperature/CO_2 driven) drought impacts
Low Deviation-Positive Impact	Occur when small deviations from environmental baselines generate positive impacts on ecosystem functions.	Climate change (human societies in very cold environments) Small wildfires that prevent catastrophic megafires

Table 2. Proposed minimum reporting standards for interoperability of disturbance investigations.

Ecosystem Properties	Reference Disturbance Properties (Reported for both Driver and Impact)	Temporal Disturbance Properties (Reported for both Driver and Impact)	Spatial Disturbance Properties (Reported for both Driver and Impact)
Ecotone	Reference Baseline State	Duration	Coordinates
Successional State	Method for determining baseline state	Rate of onset	Scale of study
Resistance	Intensity (deviation from mean or baseline)	Rate of decline	Scale of disturbance
Resilience		Variability through time	Area of extent
Recovery			Variability through space
Temporal Stability			
Method and input variables for determining resistance, resilience, recovery, and temporal stability (recommend Hillebrand et al 2018)			