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Remote sensing the vulnerability of vegetation in natural terrestrial ecosystems

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A B S T R A C T

Climate change is altering the species composition, structure, and function of vegetation in natural terrestrial ecosystems. These changes can also impact the essential ecosystem goods and services derived from these ecosystems. Following disturbances, remote-sensing datasets have been used to monitor the disturbance and describe antecedent conditions as a means of understanding vulnerability to change. To a lesser extent, they have also been used to predict when desired ecosystems are vulnerable to degradation or loss. In this paper, we review studies that have applied remote sensing imagery to characterize vegetation vulnerability in both retrospective and prospective modes. We first review vulnerability research in natural terrestrial ecosystems including temperate forests, tropical forests, boreal forests, semi-arid lands, coastal areas, and the arctic. We then evaluate whether remote sensing can evaluate vulnerability sufficiently in advance of future events in order to allow the implementation of mitigation strategies, or whether it can only describe antecedent conditions *a posteriori*. The majority of existing research has evaluated vulnerability retrospectively, but key studies highlight the considerable potential for the development of early warnings of future vulnerability. We conclude that future research needs to focus on the development of a greater number of remotely sensed metrics to be used in a prospective mode in assessing vulnerability of terrestrial vegetation under change.

1. Introduction

Climate change has modified disturbance regimes, altering the frequency, duration, and intensity of ecological disturbance processes (Bergeron & Archambault, 1993; Chapin et al., 2000; Flannigan, Stocks, & Wotton, 2000; Goetz, Bunn, Fiske, & Houghton, 2005; Westerling, Turner, Smithwick, Romme, & Ryan, 2011). Simultaneously, the ecological ranges of many tree species are changing as a function of climate change (Chmura et al., 2011; Crimmins, Dobrowski, Greenberg, Abatzogluo, & Mynseberge, 2011; Linder et al., 2010). These changes can push natural ecosystems outside their historic range of variability (Breshears et al., 2005; Landres, Morgan, & Swanson, 1999; Swetnam, Allen, & Betancourt, 1999), potentially resulting in inelastic regime shifts (Fig. 1, Beisner, Haydon, & Cuddington, 2003; Schefferm & Carpenter, 2003; Folke et al., 2004; McLauchlan et al., 2014). These changes in the distribution, structure, and function of terrestrial vegetation may result in a potential loss of desired natural capital in the form of specific ecosystem goods and services (Table 1), leading to wider social-economic and ecosystem impacts (Costanza & Daley, 1991; Costanza et al., 1997; de Groot, Wilson, & Boumans, 2002; Schröter et al., 2005). Disturbance regimes and species distributions are naturally dynamic (Carcaillet et al., 2001; Davis & Shaw, 2001; Nowak, Nowak, Tausch, & Wigand, 1994; Whitlock, Shafer, & Marlon, 2003), providing challenges in understanding the vulnerability of the associated ecosystem goods and services to climate change (Schröter et al., 2005). Considerable interest has focused on identifying if, where, and when the ecosystem goods and services are impacted by degradation or loss of the relevant terrestrial ecosystem (NRC, 2010). Given the large spatial scales over which terrestrial vegetation is evaluated and monitored, remote sensing is a logical tool to evaluate their vulnerability. Changes that are too subtle to notice at the local level may be significant when summarized at the synoptic scales captured by remote sensing data. However, given most ecosystem goods and services are not directly measurable by remote sensing datasets (Table 1), a challenge for the remote sensing community is to

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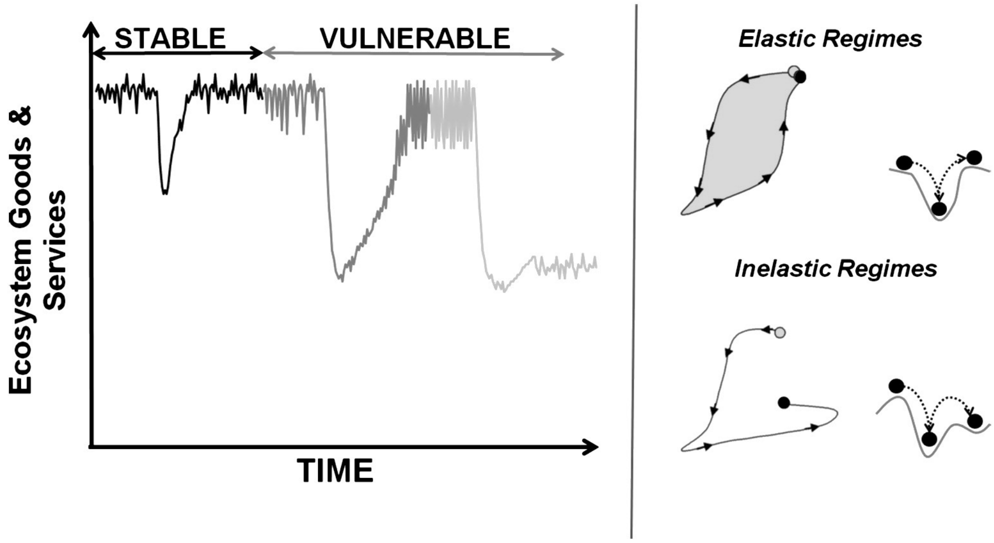

Fig. 1. Under stable conditions, a disturbance will perturb the system but will elastically return the system to pre-perturbation conditions. In a moderately vulnerable condition, increased variability may occur. Although disturbances may cause more pronounced impacts, the system will likely elastically return to pre-perturbed conditions; likely over longer time intervals and with increased variability. A highly vulnerable system has reached an ecological "tipping point" where a perturbation produces an inelastic change, leading to a new regime and potentially a complete loss in the original ecosystem service. Mitigation and adaptation strategies can lead to alternate regimes on a gradient, where the original (to a lesser degree) or alternate ecosystem goods and services may be attainable. The elasticity-hysteresis concepts are adapted from Schefferm and Carpenter (2003) and Folke et al. (2004).

identify quantitative metrics that can mechanistically bridge between the observed climate change impacts on natural terrestrial vegetation and the associated ecosystem goods and services (Fig. 2, Table 2).

Vulnerability indicators are often developed in order to describe the degree to which a system is susceptible to being impacted by future change (Alessa, Kliskey, & Brown, 2008; Alessa, Kliskey, Lammers, et al., 2008; Cutter, 1996; Hinkel, 2011; Ionescu, Klein, Hinkel, Kavi Kumar, & Klein, 2009; Timmerman, 1981; Villa & McLeod, 2002). Although hundreds of case-specific definitions of vulnerability have been created (Hinkel, 2011; Janssen & Ostrom, 2006; Linder et al., 2010), a review of these formulations is beyond the scope of this study. For the purposes of this review, we simply define vulnerability indicators as any quantitative metric using active or passive remotely sensed data that can be used to infer a "*probabilistic measure of possible future harm*" (Hinkel, 2011; Turner et al., 2003). For example, commonly accepted definitions of harm could include species mortality and economic loss; where a remote sensing analogue could be decreased primary productivity of a critical tree species or crop. In terms of climate change research, vulnerability indicators are intended to describe the susceptibility of the system to climate variability and extremes

Table 1
Common ecosystem goods and services.

Category	Example Ecosystem Goods and Services
Water supply, availability, and filtration	Quantity and quality of fresh water for reservoirs, irrigation, and industry [1, 2, 6, 7, 8, 9]
	Storage of water reserves in reservoirs, aquifers, and watersheds [1,2, 5, 7, 9]
	Drainage and irrigation [1,2]
	Water purification [4, 7]
	Snowpack depth, coverage, and ablation rates [3]
Erosion control	Soil retention by vegetation on steep slopes, reduction of erosion removal processes by wind and water [1,5, 7]
Waste processing	Removal and reduction of pollutants in watersheds [1, 5, 7, 9]
	Reduction of noise, dust, and fire pollutants in airsheds [2]
	Decomposition and detoxification [4]
Soils	Maintaining soil properties for agriculture, forestry, and recreation [2, 8]
Vegetation biodiversity. productivity, and reproduction: timber supply, food supply, and bioenergy supply	Quantity and quality of timber for paper, specialty wood products, and lumber [1,2, 7]
	Agricultural livestock and crop yields, fodder, fisheries, and bee hives [1,2, 5, 7]
	Wild terrestrial foods: game animals, wild fisheries [7]
	Seed dispersal and pollination of wildflowers and crops [1, 2, 4, 7, 9]
	Disease and pest regulation [7]
	Production of bioenergy crops, fiber, and fuels [3, 7]
Nutrient and biogeochemical cycling	Photosynthesis, decomposition, and nitrogen fixation [1, 6]
	Carbon sequestration and storage [3, 8]
Genetic resources	Harvest of plants for medicinal purposes [1,2, 7, 9]
Gas exchange	Maintenance of good air quality [2]
Disturbance dampening	The composition and structure of the vegetation (e.g., coral reefs, wetlands) can act to reduce the impacts of storms, floods, and droughts [1, 5, 7, 8]
	Establishment of refugia and seed banks [2]
Recreation and cultural sites	Access to non-commercial recreation and cultural sites such as State and National Parks, National Monuments. [1,2, 5]
	Sustainability of fishing, swimming, hiking, and skiing access areas [1,2,3, 9]
	Aesthetic, spiritual, and religious sites [7]
	Sites of scientific and educational interest [1,2]

[1]Costanza et al. (1997), [2]de Groot et al. (2002), [3]Schröter et al. (2005), [4] Kremen (2005), [5] Costanza and Daley (1991)
[6] Kessler, Salwasser, Cartwright, and Caplan (1992), [7] Carpenter et al. (2009), [8] Nelson et al. (2009), [9] Boyd and Spencer (2007)