A Landscape Disturbance Matrix for Conserving Biodiversity

Discussion Paper

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Abstract

No single disturbance regime is suitable for maintaining ecological patterns and processes across an entire landscape when viewed broadly from an ecological perspective. Some species may require high-frequency and high-intensity disturbance, while others may require low-frequency and low-intensity disturbance. Across a large landscape, specific sites with certain features, slopes, and topography also provide important elements for the structure and function of the landscape. These sites, coupled with varying time since disturbance, provide diverse spatial mosaics across landscapes and are essential for biodiversity. Traditional land management has employed a simplistic view of natural processes. The result on large landscapes is that patterns derived from these processes are not comprehensively understood, accepted, or applied. In most landscapes, traditional management has not promoted heterogeneity so that all possible conditions are represented. However, based on all available evidence, creating heterogeneity and a shifting mosaic across the landscape should be a primary objective if conservation of biodiversity is the goal. This article introduces the concept of the landscape disturbance matrix (LDM) as a framework for strategic landscape planning that encompasses time since disturbance at multiple sites. This concept keys in on the needs of priority wildlife species, which have varying responses to time since disturbance. In this article, a large management area in northeastern British Columbia is used to demonstrate that managing change in the landscape for multiple times since disturbance on multiple sites will promote multi-functionality and biodiversity, thereby providing an objective basis for land management planning. A forward planning approach such as the LDM also provides a foundation for ecological resilience and disturbance-absorbent landscapes, thereby allowing land managers to plan for the future based on the past and current disturbance regimes.

KEYWORDS: British Columbia; fire; heterogeneity; resource selection; shifting mosaic

Introduction

Disturbance processes are critical to ecosystem function and resilience, and they should be integrated into comprehensive management plans that can account for spatial and temporal patterns (Agee & Huff 1987; Turner et al. 1993). Disturbance can be defined as a disruption or perturbation to an ecosystem, community, or population structure that is caused by any

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relatively discrete event in time and space, which changes resources (White & Pickett 1985). These discrete events over time begin to merge into pattern-driving processes that are more similar to climate than to a single discrete event. In this article, the primary example of fire is used to demonstrate the approach to restoring disturbance pattern and process in a landscape; therefore, fire is considered more from a landscape pattern-driving process than from a single discrete event. Fire is a useful example of a disturbance that is a fundamental process within many ecosystems. Fire as a "natural" disturbance process includes anthropogenic ignitions (historical) and can produce heterogeneity across many spatial and temporal scales, which promotes biological diversity (Wiens 1997). Fire-driven heterogeneity is important to hydrology (Ludwig et al. 2000; Belnap et al. 2005), fire behaviour (Archibald et al. 2005; Kerby et al. 2007; Fuhlendorf et al. 2009), grazing patterns (Senft et al. 1987; Fuhlendorf & Engle 2004; Fryxell et al. 2005), soil aggregate stability and nutrient cycling (Bird et al. 2002; Augustine et al. 2003; Anderson et al. 2006), ecosystem stability (Holling & Meffe 1996; van de Koppel & Rietkerk 2004; Hovick et al. 2015), and species invasion (Deutschewitz et al. 2003; Cummings et al. 2007).

Fire plays an integral role as a driver of landscape function and processes, yet its management at broad scales has long been contentious and lacking in long-term planning (Goldammer & Furyaev 1996; van Wilgen et al. 2004). Across a large and complex landscape, fire varies in space and time, which results in a shifting mosaic of discrete patches with different fire return intervals and amounts of time since the most recent fire. Shifting mosaics produce patterns across the landscape that contribute to heterogeneity and biodiversity (Fuhlendorf & Engle 2001; Fuhlendorf et al. 2006). Some species require conditions within the landscape that are created by high-frequency and/or high-intensity disturbance, while others may depend on conditions that require low-disturbance frequency and/or intensity, which suggests that regional conservation should focus on maintaining a diverse landscape that includes a full array of conditions (Rowe & Scotter 1973; Fuhlendorf et al. 2012).

Photo credit: S. E. R. Leverkus, 2008

Debates over appropriate fire management plans have occurred throughout North America and in other regions in the world, including the Kakadu National Park in Australia, Kruger National Park in South Africa, and forested areas in Sweden (Angelstam 1998; Bowman et al. 2004; White et al. 2011). Fire management has been practiced in African savannas for decades, but many issues have been associated with its adoption and application, such as unplanned fires, presence of invasive species, and lack of social acceptance (van Wilgen et al. 2004, 2011). Clearly, since large conservation areas often have multiple objectives, heterogeneity should be included as a fundamental concept in a management plan. However, comprehensive evaluation of management plans has long been hampered by a limitation in the understanding of the importance of heterogeneity and by limitations in technology to directly apply it to large scales (Fuhlendorf et al. 2012; van Wilgen 2013). It is critical that large-scale plans have support from diverse stakeholders, while still being flexible and efficient (Schmiegelow et al. 2006; van Wilgen et al. 2011).

The approach taken in this article is to develop a plan for a landscape management disturbance regime that maintains patterns and processes. This regime will inherently address multiple management and ecological objectives through space and time (Lamprey 1963; Heady 1966; Schmiegelow et al. 2006; Fuhlendorf et al. 2012). The model presented is based on an adaptable framework that can be altered and adjusted for implementation across many ecosystems, disturbance regimes, and management objectives (Cissel et al. 1999; Brockett et al. 2001; McKenzie et al. 2011). The conservation of biodiversity by maintaining heterogeneity and shifting mosaics is considered a primary objective. To this end, the landscape disturbance matrix (LDM) is introduced as a framework for strategic landscape-level planning that encompasses time since fire (disturbance) over multiple sites with varying responses by species. The specific objectives are 1) to present and review a novel approach to managing natural disturbance based on historical and current conditions that is integrated with land management priorities to meet future objectives, and 2) to demonstrate application of the approach as a case study for the 6.4 million hectare Muskwa-Kechika Management Area (M-KMA) of northeastern British Columbia, including discussion of the challenges and limitations of the approach.

Landscape disturbance matrices

What are landscape disturbance matrices?

Landscape disturbance matrices are a tool for organizing past and future disturbances and ecological processes through space and time as an important first step in efficiently managing patterns and shifting mosaics that are critical for ecosystem structure and function (Turner et al. 1993; Burton et al. 2008; Fuhlendorf et al. 2012). Landscape disturbance matrices present a framework of multiple matrices for sites defined by topoedaphic or landscape features (e.g., soil, aspect, slope, or watersheds), integrated with time since disturbance—in this case, fire (Table 1). The parameter of time-since-fire categories and the proportion of the landscape in each category are used as the foundation of LDMs. However, alternative and additional parameters could be used for other ecosystems and disturbance regimes, as warranted. The size of each topoedaphic site, the geographical area burned (disturbed), the number of potential years it would take to burn all of each site if the conditions were the same as in the past, and the historical fire return intervals are captured within the LDM.

Table 1. An example of the foundational matrix

	Watershed 1	Aspect				Watershed 1	Aspect			
current ha (burnable) area in	Site 1	North	East	South	West	Site 2	North	East	South	West
0 - 2 years since fire										
2 - 10 years since fire										
10 - 25 years since fire										
25 - 50 years since fire										
50 - 90 years since fire										
>90 years since fire										
desired ha (burnable) area in										
0 - 2 years since fire										
2 - 10 years since fire										
10 - 25 years since fire										
25 - 50 years since fire										
50 - 90 years since fire										
>90 years since fire										

Design and development of landscape disturbance matrices

Development of an LDM requires four steps. The first is to develop an inventory of recent disturbances by determining contemporary fire history. This is exclusive of the evolutionary influence of fire activity on ecosystems. In the example in this article, a fire history is constructed, and ecosystem conditions of an area targeted for disturbance management are inventoried. An ecosystem condition inventory focuses on recent fire history (e.g., last 50–100 years) and helps define the current status of the landscape relative to time since fire. Acquiring the spatial extent of past fires in relation to the selected sites or hierarchical levels is an obvious and desirable approach for developing a description of current fire regimes and recent history. Additional fire data may be available from the BC Wildfire Service historical fire perimeters (http://maps.gov.bc.ca/ess/sv/imapbc/), MODIS (http://modis.gsfc.nasa.gov/, http://modis-fire.umd.edu/index.html), or the Canadian Council on Geomatics and Natural Resources Canada (http://www.geobase.ca/geobase/en/index.html). Additional features that can be considered include aspect, slope, elevation, treeline influence, presence of permafrost, soils, and land cover; however, no single classification system is perfect. If existing data are not available, an approximation of topoedaphic classification can be developed using Digital Elevation Models. Potential vegetation can be used based on existing classification frameworks (e.g., Biogeoclimatic Ecosystem Classification, LANDFIRE [USDA & USDOI 2013], USDA [2012, 2013] ecological site descriptions) or remote sensing and field classifications. Additional indicators of the historical importance of fire in quantifying specific regimes might include the presence or absence of certain species, communities, and processes (pyric herbivory); firebrands, firescars, and fire barriers (vegetation layers such as the British Columbia Vegetation Resources Inventory data https://www.for.gov.bc.ca/hts/vridata/ or BC Wildfire Service historical fire perimeters http://maps.gov.bc.ca/ess/sv/imapbc/); lightning strike density and ignition records (Environment Canada https://ec.gc.ca/foudre-lightning/default.asp?lang=En&n=D88E34E8-1); and place names, linguistics, cultural artwork, and oral accounts by First Nations, Aboriginal, and indigenous peoples and long-time residents of an area (Anderson 1975; Pyne 1997; Miller et al. 2007; Garde 2009). Vegetation types on historical survey maps and temporally paired aerial photos provide recent history data and change through time (Kay et al. 1999; Klement et al. 2001).

The second step is to identify the historical spatial and temporal range and variability of disturbance regimes (fire regimes, in this example) for each site, resulting in a historical matrix of disturbance for time frames longer than the last 100 years. This is important for identifying the range of patch sizes relevant to current and future management objectives. Historical natural fire regimes and measures of departure from those regimes are descriptive. Also needed is a measure of what structures and what structural patterns are part of the historical fire regimes and in what arrangement over time on the landscape. Multiple types of data and evidence can assist in identifying the historical range and variability of fire for each site. For example, Reid & Fuhlendorf (2011) used LANDFIRE to compare historical fire regimes to the current fire regime of the Charles M. Russell National Wildlife Refuge in Montana. Critical historical reconstructions can also be conducted by using vegetation reconstructive techniques such as pollen analysis, dendrochronological analysis, and analyses of preserved packrat middens (Larsen & MacDonald 1998; Barton et al. 2001; Whitlock & Knox 2002; Pyne 2007). While these methods are useful for delineating estimated fire frequency and type (surface versus stand replacing), they are still limited in defining the true dynamic nature of complete fire regimes, which suggests the need for some interpretation. The use of these lines of evidence extends well beyond the current climate regime and is relevant only if the landscape analysis considers management strategies that bridge multiple climate regimes.

The third step is to determine the spatio-temporal scale of management and to develop specific objectives based on a combination of discussions, review of management plans, and input from stakeholders (Peck & Currie 1992; Parminter 1993). The scales are selected by the developers of the matrices and can be nested if appropriate. The stakeholder group is critical for filling knowledge gaps about disturbance patterns and for fully integrating management objectives into the LDM framework. Their input is obtained through meetings, reviews of plans, and involvement in the development of the LDM. Once landscape objectives are determined, a comparison can be drawn between the historical range of variability and current conditions, which can lead to the development of desired conditions to meet the objectives. Resource selection and requirements of priority species will need to be reviewed and interpreted. The LDM offers a framework that ideally requires communication among all stakeholders throughout the development phase to define goals and management objectives directed at achieving landscape-level multi-functionality. It could be argued that identifying the resource requirements of priority species should be the first step; however, it is foundational to understand the historical and current distribution of fire, or disturbance, across the landscape as a first step, followed by discussion on what amount is required and/or desired to meet the resource requirements of priority species and other landscape objectives.

The fourth step is to develop a final matrix that outlines the desired distribution of time since disturbance across the landscape while acknowledging the resource requirements of the target species. In this final matrix, historical range of variability forms only part of the decision-making process. Disturbance patch size, patch distribution across the landscape, and resource requirements of species combine to form a theoretical foundation upon which to base current and future fire management (Haufler et al. 1996). Land managers can use the matrix of desired conditions as an adaptive management tool to drive future prescribed fire and to alter them as wildfires occur. These matrices can be developed at several hierarchical scales to ensure that the spatial arrangement of disturbance matches that of target conditions.

Landscape disturbance matrices for the Muskwa-Kechika management area

The most extensive, intact, terrestrial biome on earth is the circumboreal forest, which includes an estimated 100 000+ species (Zasada et al. 1997; Schmiegelow et al. 2006; Burton et al. 2008; Flannigan et al. 2009). Fire is a dominant ecosystem driver in the boreal forest. It has been argued that anthropogenic fire and lightning since the last Ice Age have resulted in the current patchwork mosaic pattern across the boreal forest (Rowe & Scotter 1973; Goldammer & Furyaev 1996; Stocks et al. 2003). Large-scale crown fires and high-intensity surface fires occurred in pre-settlement Canadian boreal landscapes on fire cycles of 50–700 years (Heinselman 1981; Stocks et al. 2003). Fire has always been a dominant process across this landscape as a result of lightning-ignited fire combined with anthropogenic burning by indigenous people (Lewis 1978; Lewis & Ferguson 1988). Leverkus (2015) developed a fire history for the boreal forest in northeastern British Columbia, Canada, which focused on three scales (regional, sub-regional, and watersheds), following the methodology of Stocks et al. (2003). The sub-regional scale was the Muskwa-Kechika Management Area (M-KMA) (Figure 1).

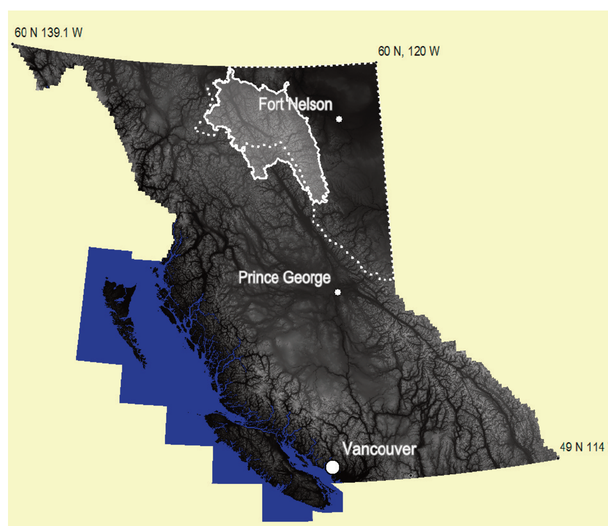

Figure 1

The M-KMA was intended to serve as a model that balances conservation of the environment and wilderness with human activities, primarily resource extraction and tourism (http://www.muskwa-kechika.com/management-area/). The Muskwa-Kechika Wildlife Management Plan (M-KWMP) is the higher level guidance document that was developed and approved by the British Columbia government in 2009; it suggests that in the absence of fire, biodiversity would be reduced in the M-KMA (B.C. Ministry of Environment 2009a). It further states that early seral grassland components, or sites maintained by recent time since fire, are required on a continual basis to support numerous species within the M-KMA (B.C. Ministry of Environment 2009a).

The first matrix demonstrating the distribution of disturbance, wildfire, and prescribed fire in recent history is presented across eight areas in northeastern British Columbia: the M-KMA and the seven largest watersheds within it (Table 2) As of 2012, in 2.4% of the M-KMA, there had been 0–10 years since fire, whereas in 77% there had been more than 90 years since fire (Table 2). Data were sourced from the BC Wildfire Service (wildfire from 1922 to 2012) and the B.C. Fish and Wildlife Branch (prescribed fire from 1980 to 2008). The historical range and variability of fire for each site within the M-KMA were not available; however, 91 years of fire history data were analyzed in the first step of the LDM. The current disturbance pattern is highly variable: north-facing slopes experience infrequent fire, while some south-facing slopes have a high frequency of burning (Leverkus 2015). The time required to burn all the M-KMA and the seven watersheds is estimated to range from 164 to 949 years based on analysis of available data (Leverkus 2015).

Table 2 . Fire distribution

Current (burnable) area (ha) in	M-KMA[a]	Liard	Kechika	Rabbit	Toad	Ft Nelson	Halfway	Finlay
0-2 years since fire	0.4	0.0	0.9	0.0	0.1	0.6	0.0	0.0
2-10 years since fire	2.0	1.4	4.5	0.0	4.5	1.9	1.0	0.4
10-25 years since fire	3.0	4.1	1.4	0.1	7.6	7.8	5.2	1.2
25-50 years since fire	8.9	36.0	6.4	3.1	16.9	9.8	2.6	7.0
50-90 years since fire	8.6	13.3	20.4	7.4	8.0	5.6	0.7	2.1
> 90 years since fire	76.7	44.7	65.7	89.4	60.2	73.6	90.4	89.3
unknown	0.6	0.5	0.6	0.0	2.9	0.9	0.0	0.0

Note: The current distribution of fire across the Muskwa-Kechika Management Area and the seven largest watersheds within the M-KMA with values representing percent burned of the total burnable area (modified from Leverkus 2015).

The spatial extent of the M-KMA LDM is the boundary of the M-KMA with its seven largest watersheds. The M-KWMP and the Fort Nelson Land and Resource Management Plan (LRMP) (http://www.for.gov.bc.ca/dfn/ForestPractices/hlp2.htm) were reviewed to determine the priority species within the M-KMA. The development of the LRMP (1997) and the M-KMA (1998) involved many years of stakeholder and agency meetings, consultation, and involvement. Therefore, the M-KWMP review provided sufficient detail and information from the various agencies and stakeholders operating in the M-KMA to build the third matrix of the LDM. The resource requirements of the 24 priority species and three additional regionally important species within the M-KMA have been generalized, with a focus on how fire is thought to influence land cover, resource selection, and habitat maintenance (Table 3, Table 4). Time since fire drives the vegetation structure in parts of the alpine and subalpine and most parts of the open rangeland and open forest within the M-KMA (Geertsema and Pojar 2007; Burton et al. 2008; Fuhlendorf et al. 2009). Open rangeland and open forest—defined as natural terrestrial vegetation types in which cover and energy flow are not dominated by trees—are reliant on fire in the M-KMA, and the diverse priority species within the M-KMA require varying time since fire for their preferred resource selection (Table 3, Table 4) (Natcher 2004). The 24 priority species and three regionally important species in the M-KMA require different resources and land cover during different phases of their life cycles, from birthing grounds to foraging areas to seasonally used terrain.

Table 3. Resource selection of habitat preference

		Resource Selection of Habitat Preference				
Species	**Provincial Listing**	**Bare rock**	**Open range-land / alpine / sub-alpine**	**Open forest**	**Dense forest**	**Water / riparian**
Humans	yellow					
Horse	yellow					
Wood bison	red					
Plains bison	red					
Moose	yellow					
Elk	yellow					
Woodland caribou	red & blue					
Mountain goat	yellow					
Thinhorn stone sheep	yellow					
Grizzly bear	blue					
Gray wolf	yellow					
Wolverine	blue					
Fisher	blue					
Northern myotis	blue					
Lesser sandhill crane	yellow					
Short-eared owl	blue					
Peregrine falcon	red					
Bay-breasted warbler	red					
Cape may warbler	red					
Black-throated green warbler	blue					
Connecticut warbler	red					
Bull trout	blue					
Lake trout	yellow					
Arctic grayling	yellow					
Rainbow trout	yellow					
Northern pike	yellow					
Western toad	yellow					

Notes: Priority wildlife species of the Muskwa-Kechika Management Area and their resource selection of habitat preference, adapted from Lamprey 1963 and Heady 1966 (BC Ministry of Environment 2009a and 2009b). Listings are in reference to the species' Provincial Conservation Status Rank (BC Ministry of Environment, 2009a and 2009b). Red-listed includes any ecological community, and indigenous species and subspecies that is extirpated, endangered, or threatened in British Columbia whereas blue-listed includes any ecological community, and indigenous species and subspecies considered to be of special concern (formerly vulnerable) in British Columbia (Province of British Columbia 2013). Yellow-listed species and communities are not currently at risk in British Columbia. Caribou are red and blue-listed in the Muskwa-Kechika Wildlife Management Plan (BC Ministry of Environment 2009a and 2009b). Humans and horses have been added as they are present in the M-KMA.

Varied time since fire influences species distribution and resource selection across large landscapes by causing varied access to and abundance of resources. These resources include (Table 4):

- browse, forage, insects, fruits, and berries (Seip & Bunnell 1984, 1985; Munro et al. 2006; Ciarniello et al. 2007; Stevens et al. 2007)
- availability and abundance of prey species and their resource requirements (Boutin et al. 2003; Sullivan et al. 2006; Hatler and Beal 2010)

- hunting areas and riparian areas, including access to mineral licks (Krebs et al. 1995; Hatler and Beal 2010)
- host plants and vegetation that is important for invertebrate life cycles (Baum & Sharber 2012)
- vertical structure such as coarse woody debris, snags, rotting trees, and layered overhead vegetation for shelter, perching, denning, hibernacula, roosting, cover, escape, breeding, lambing, calving, nursery and rearing sites, naissance, migrating staging areas, rubbing posts, and scent posts (Seip & Bunnell 1984; Hobson & Schieck 1999; Schieck & Hobson 2000; Fisher & Wilkinson 2005; Hatler & Beal 2010)
- habitat connectivity, matrix, and suitability (B.C. Ministry of Environment 2009a, 2009b; Holsinger & Keane 2011)
- proximity to escape terrain, which may be critical for a species' survival, whereas another species may require considerable cover for thermal regulation (Blood & Backhouse 1998; Walker et al. 2006) (Table 3)

Table 4: Habitat/Vegetation type resource selection across species

Species	Habitat/Vegetation Type Resource Selection	Citation
Humans, *Homo sapiens*	rock: viewscapes, recreational activities, hunting	Fort Nelson Land and Resource Management Plan 2009
	alpine: hiking, viewscapes, hunting, wildlife viewing	Meidinger & Lewis 1983; Fort Nelson Land and Resource Management Plan 2009
	sub-alpine: hunting, hiking, viewscapes	Meidinger & Lewis 1983; Fort Nelson Land and Resource Management Plan 2009
	open rangeland: hunting, hiking, viewscapes, trapping	Meidinger & Lewis 1983; Fort Nelson Land and Resource Management Plan 2009; Hatler & Beal 2010
	open forest: trapping, hunting, recreational activities	Meidinger & Lewis 1983; Fort Nelson Land and Resource Management Plan 2009; Hatler & Beal 2010
	dense forest: trapping, hunting	Fort Nelson Land and Resource Management Plan 2009; Hatler & Beal 2010
	muskeg/riparian areas/rivers/lakes: trapping, transportation, fishing, hunting	Fort Nelson Land and Resource Management Plan 2009; Hatler & Beal 2010
Horse, *Equus caballus*	open rangeland: foraging	Haber 1988; Burns 2001; Beever et al. 2008; Edwards 2008; Vince 2011; Girard et al. 2013
	open forest: foraging, cover	Edwards 2008; Beever et al. 2008; Vince 2011; Girard et al. 2013
Wood bison, *Bison bison athabascae*	open rangeland/sedge meadows: foraging and wallowing	Soper 1941; Larter & Gates 1991; Harper & Gates 1999; Harper et al. 2000; Fortin et al. 2002; BC Ministry of Environment 2009; Goddard 2011
	open forest: rutting, rubbing and foraging	Soper 1941; Larter & Gates 1991; Harper et al. 2000; Fortin et al. 2002
	dense forest: cover, rubbing and forage	Soper 1941; Larter & Gates 1991; BC Ministry of Environment 2009a
	muskeg/riparian areas: foraging and wallowing	Soper 1941; DeLong et al. 1991; Larter & Gates 1991; Harper et al. 2000; Fortin et al. 2002

Table 4: (Continued)

Species	Habitat/Vegetation Type Resource Selection	Citation
Plains bison, *Bison bison bison*	open rangeland/sedge meadows: forage	Pojar & Stewart 1991a; Fuhlendorf et al. 2010; BC Ministry of Environment 2009a; Goddard 2011
	dense forest: cover and forage	BC Ministry of Environment 2009a
	muskeg/riparian areas: forage	Pojar & Stewart 1991a; Fuhlendorf et al. 2010
Moose, *Alces alces andersoni*	alpine	Meidinger & Lewis 1983; Gustine & Parker 2008; BC Ministry of Environment 2009a
	subalpine: winter use	BC Ministry of Environment 2009a
	open rangeland: forage	DeLong et al. 1991; Pojar & Stewart 1991a; Nappi et al. 2004; Fisher & Wilkinson 2005; Gustine et al. 2006b; BC Ministry of Environment 2009a; Goddard 2011
	open forest	DeByle 1984; DeLong et al. 1991; Pojar & Stewart 1991a and 1991b; Fisher & Wilkinson 2005; BC Ministry of Environment 2009a
	dense forest: forage and thermal cover	DeLong et al. 1991; BC Ministry of Environment 2009a
	muskeg/riparian: forage	DeLong et al. 1991; Pojar & Stewart 1991a; BC Ministry of Environment 2009a
Elk, *Cervus elaphus*	alpine	Pojar & Stewart 1991b
	subalpine: winter use	Seip & Bunnell 1985; Gustine & Parker 2008; BC Ministry of Environment 2009a
	open rangeland: foraging	Kufeld 1973; DeByle 1984; DeLong et al. 1991; Peck & Peek 1991; Peck & Currie 1992; Gustine et al. 2006b; Christianson & Creel 2007; Sawyer et al. 2007; Van Dyke & Darragh 2007; Keigley & Frisina 2008; Long et al. 2008; Yukon Elk Management Planning Team 2008; BC Ministry of Environment 2009a; Long et al. 2009; Goddard 2011
	open forest: cover, foraging and browse (winter), rubbing	DeByle 1984; Seip & Bunnell 1984; DeLong et al. 1991; Peck & Peek 1991; Pojar & Stewart 1991a; White et al. 1998; White et al. 2003; Sachro et al. 2005; Christianson & Creel 2007; Keigley & Frisina 2008; Long et al. 2008; Yukon Elk Management Planning Team 2008
	dense forest: thermal cover, hiding and browse (winter), rubbing	DeByle 1984; Seip & Bunnell 1984; Peck & Peek 1991; Keigley & Frisina 2008

Table 4: (Continued)

Species	Habitat/Vegetation Type Resource Selection	Citation
Woodland caribou, *Rangifer tarandus caribou*	alpine: summer use and winter use	Seip & Bunnell 1985; Pojar & Stewart 1991b; Gustine et al. 2006a; Gustine & Parker 2008; BC Ministry of Environment 2009a
	subalpine	BC Ministry of Environment 2009a
	open rangeland	Pojar & Stewart 1991b
	open forest	DeLong et al. 1991; Pojar & Stewart 1991a, Fisher & Wilkinson 2005; Dalerum et al. 2007; BC Ministry of Environment 2009a
	dense forest: winter use	DeLong et al. 1991; Fisher & Wilkinson 2005; Gustine et al. 2006a; Dalerum et al. 2007; Gustine & Parker 2008, BC Ministry of Environment 2009a
	muskeg/riparian	Pojar & Stewart 1991a; BC Ministry of Environment 2009a
Mountain goat, *Oreanmnos americanus*	rock: escape terrain	Pojar & Stewart 1991b; Hamel & Côté 2007; BC Ministry of Environment 2009a
	alpine	Meidinger & Lewis 1983; Pojar & Stewart 1991b; Hamel & Côté 2007; BC Ministry of Environment 2009a
	open rangeland	DeLong et al. 1991; Pojar & Stewart 1991b; Peck & Currie 1992; Goddard 2011
Stone's sheep, *Ovis dalli stonei*	rock: escape terrain and mineral licks	Pojar & Stewart 1991a; Walker et al. 2006; BC Ministry of Environment 2009a; Sittler 2013
	alpine: winter range, yearly	Meidinger & Lewis 1983; Seip & Bunnell 1984; Seip & Bunnell 1985; Pojar & Stewart 1991b; Walker et al. 2006; BC Ministry of Environment 2009a
	open rangeland/ burned sub-alpine: foraging	Meidinger & Lewis 1983; Seip & Bunnell 1984; Seip & Bunnell 1985; DeLong et al. 1991; Pojar & Stewart 1991a; Pojar & Stewart 1991b; Gustine et al. 2006b; Walker et al . 2007; BC Ministry of Environment 2009a; Goddard 2011; Vince 2011
	dense forest: escape terrain	BC Ministry of Environment 2009a

Table 4: (Continued)

Species	Habitat/Vegetation Type Resource Selection	Citation
Grizzly bear, *Ursus arctos*	alpine: root digging	Meidinger & Lewis 1983; Pojar & Stewart 1991b; Munro et al. 2006; BC Ministry of Environment 2009a
	subalpine	BC Ministry of Environment 2009a
	open rangeland: root digging	DeLong et al. 1991; Pojar & Stewart 1991a; Pojar & Stewart 1991b; Gustine et al. 2006b; Munro et al. 2006; BC Ministry of Environment 2009a
	open forest: insect feeding and frugivory dense forest: selection for spruce forests	Munro et al. 2006; BC Ministry of Environment 2009a; Ciarniello et al. 2007; BC Ministry of Environment 2009a
	muskeg/riparian area	DeLong et al. 1991; Pojar & Stewart 1991a; BC Ministry of Environment 2009a, 2009b
Gray wolf, *Canis lupus*	alpine	BC Ministry of Environment 2009a
	subalpine	BC Ministry of Environment 2009a
	open rangeland	DeLong et al. 1991; Pojar & Stewart 1991a; Fisher & Wilkinson 2005; Gustine et al. 2006b; BC Ministry of Environment 2009a
	open forest	DeLong et al. 1991; Pojar & Stewart 1991a; BC Ministry of Environment 2009a
	dense forest	DeLong et al. 1991; BC Ministry of Environment 2009a
	muskeg/riparian area	DeLong et al. 1991; Pojar & Stewart 1991a; BC Ministry of Environment 2009a
Wolverine, *Gulo gulo*	alpine: denning and rearing kits	Lofroth & Krebs 2007
	subalpine: summer use	Krebs et al. 2007
	open rangeland: dispersal corridors	Pojar & Stewart 1991a; Dalerum et al. 2008
	open forest: dispersal corridors, winter use	Pojar & Stewart 1991a; Krebs et al. 2007; Dalerum et al. 2008
	dense forest	DeLong et al. 1991
	resource selection linked to availability and distribution of food resources	Hatler & Beal 2010
Fisher, *Martes pennanti*	open rangeland: foraging	Fisher & Wilkinson 2005; Hatler & Beal 2010
	open forest: hunting	Boutin et al. 2003; Sullivan et al . 2006
	dense forest: foraging, winter use	Boutin et al. 2003; Fisher & Wilkinson 2005; Sullivan et al. 2006; Hatler & Beal 2010
	muskeg/riparian area: foraging	Hatler & Beal 2010

Table 4: (Continued)

Species	Habitat/Vegetation Type Resource Selection	Citation
Northern myotis, *Myotis septentrionalis*	open rangeland: foraging (insectivore)	Wilsmann et al. 1996; Fisher & Wilkinson 2005
	open forest: roosting, foraging (insectivore)	DeLong et al. 1991; Wilsmann et al. 1996; Ciechanowski et al. 2007; BC Ministry of Environment 2009a
	dense forest : roosting/hibernacula and foraging (insectivore)	Wilsmann et al. 1996; Fisher & Wilkinson 2005; Ciechanowaski et al. 2007
	riparian area/water: foraging (insectivore)	Wilsmann et al. 1996; BC Ministry of Environment 2009a
Lesser sandhill crane, *Grus canadensis canadensis*	open rangeland/sedge meadows: stopover sites, breeding, nesting	Cooper 1996; Blood & Backhouse 1999; International Crane Foundation
	open forest: escape cover	Blood & Backhouse 1999; International Crane Foundation
	dense forest: escape cover, resting, feeding	Campbell et al. 1990; Cooper 1996
	riparian area/wetland: nesting, loafing, roosting	Cooper 1996; Blood & Backhouse 1999; International Crane Foundation
Short-eared owl, *Asio flammeus*	alpine/tundra: nesting	Dement'ev 1951; Mikkola & Sulkava 1969; Clark 1975; BC Ministry of Environment 2009a
	open rangeland: nesting	Dement'ev 1951; Mikkola & Sulkava 1969; Clark 1975; BC Ministry of Environment 2009a
	dense forest: nesting	Dement'ev 1951; Mikkola & Sulkava 1969; Clark 1975; BC Ministry of Environment 2009a
	riparian area/water: hunting	Dement'ev 1951; Mikkola & Sulkava 1969; Clark 1975; BC Ministry of Environment 2009a
Peregrine falcon, *Falco peregrinus anatum*	rock/cliff: nesting	BC Ministry of Environment 2009a
	alpine/tundra: nesting	BC Ministry of Environment 2009a
	open rangeland: hunting	BC Ministry of Environment 2009a
Bay-breasted warbler, *Dendroica castanea*	open forest: foraging in upper canopy, nesting (300 - 400ha continuous tracts of forest minimum required), mature white spruce (pure stands or mixed with aspen, birch, balsam poplar)	Cooper et al. 1997; Blood & Backhouse 1998
	dense forest: foraging in upper canopy, nesting (300 - 400ha continuous tracts of forest minimum required), mature white spruce (pure stands or mixed with aspen, birch, balsam poplar)	Cooper et al. 1997, Blood and Backhouse 1998

Table 4: (Continued)

Species	Habitat/Vegetation Type Resource Selection	Citation
Cape may warbler, *Dendroica tigrina*	open forest (300 - 400ha continuous tracts of forest minimum required)	BC Ministry of Environment 2009a
	dense forest: breeding, foraging in upper canopy, nesting (300 - 400ha continuous tracts of forest minimum required)	Blood & Backhouse 1998; BC Ministry of Environment 2009a
	riparian area	BC Ministry of Environment 2009a
Black-throated green warbler, *Dendroica virens*	open forest: forest edge (300 - 400ha continuous tracts of forest minimum required)	DeLong et al. 1991; Blood & Backhouse 1998; BC Ministry of Environment 2009a
	dense forest: foraging in mid-to upper canopy, nesting, forest edge (300 - 400ha continuous tracts of forest minimum required)	Blood & Backhouse 1998; Schieck & Hobson 2000; BC Ministry of Environment 2009a
	muskeg/riparian area	DeLong et al. 1991; BC Ministry of Environment 2009a
Connecticut warbler, *Oporornis agilis*	open forest: ground nesting and foraging (300 - 400ha continuous tracts of forest minimum required)	Blood & Backhouse 1998; Hobson & Schieck 2009; BC Ministry of Environment 2009a
	dense forest (300 - 400ha continuous tracts of forest minimum required)	BC Ministry of Environment 2009a
	muskeg/riparian area	DeLong et al. 1991
Bull trout, *Salvelinus confluentus*	given adeqaute connectivity to robust population segments, bull trout are resilient to fire's effects	Dunham et al. 2003; Holsinger & Keane 2011
Lake trout, *Salvelinus namaycush*	riparian area	Dunham et al. 2003
Arctic grayling, *Thymallus arcticus*	riparian area	Dunham et al. 2003
Rainbow trout, *Oncorhynchus mykiss*	riparian area	Dunham et al. 2003
Northern pike, *Esox lucius*	riparian area	Dunham et al. 2003
Western toad, *Bufo boreas*	riparian area	Pojar & Stewart 1991a

Note: The priority species of the Muskwa-Kechika Management Area and additional regional priority species with their habitat, vegetation and resource selection requirements across the landscape as determined through a literature review with relevant citations listed.

Table 5. Potential distribution of time since fire

Potential target ha (burnable) area in	M-KMA	Liard	Kechika	Rabbit	Toad	Ft Nelson	Halfway	Finlay
0 - 2 years since fire	0 - 484,384 (0-10)	0 - 40,963 (0-10)	0 - 128,288 (0-10)	0 - 15,665 (0-10)	0 - 34180 (0-10)	0 - 781,88 (0-10)	0 - 29,473 (0-10)	0 - 61,049 (0-10)
2 - 10 years since fire	242,192 - 726,576 (5-15)	20,481 - 61,444 (5-15)	64,144 - 192,432 (5-15)	7,832 - 23,497 (5-15)	17,090 - 51,271 (5-15)	39,094 - 117,282 (5-15)	14,736 - 44,209 (5-15)	30,523 - 91,569 (5-15)
10 - 25 years since fire	484,384 - 968,768 (10-20)	40,963 - 81,925 (10-20)	128,288 - 256,576 (10-20)	15,665 - 31,330 (10-20)	34,180 - 68,361 (10-20)	78,188 - 156,376 (10-20)	29,473 - 58,946 (10-20)	61,046 - 122,092 (10-20)
25 - 50 years since fire	484,384 - 968,768 (10-20)	40,963 - 81,925 (10-20)	128,288 - 256,576 (10-20)	15,665 - 31,330 (10-20)	34,180 - 68,361 (10-20)	78,188 - 156,376 (10-20)	29,473 - 58,946 (10-20)	61,046 - 122,092 (10-20)
50 - 90 years since fire	726,576 - 1,453,152 (15-30)	61,444 - 122,888 (15-30)	192,432 - 384,864 (15-30)	23,497 - 46,995 (15-30)	51,271 - 102,541 (15-30)	117,282 - 234,565 (15-30)	44,209 - 88,418 (15-30)	91,569 - 183,138 (15-30)
>90 years since fire	1,210,960 - 2,664,111 (25-55)	102,407 - 225,294 (25-55)	320,720 - 705,583 (25-55)	39,162 - 86,157 (25-55)	85,451 - 187,992 (25-55)	195,471 - 430,035 (25-55)	73,682 - 162,100 (25-55)	152,615 - 335,754 (25-55)
Estimated years required to burn all	390	164	266	858	229	344	949	856

Notes: Potential distribution of time since fire across the Muskwa-Kechika Management Area and its seven largest watersheds with values in hectares and numbers in parentheses representing percent of the total burnable area (adapted from Leverkus 2015). Estimated years required to burn all burnable hectares (exclusive of rock, ice, snow and area of cloud cover from spatial analysis) is distributed across the areas of interest. The potential hectares can be manipulated to account for years of larger fire activity and to meet management objectives across the landscape.

Species in the M-KMA may be limited by climate, vegetation cover, and predation (B.C. Ministry of Environment 2009a, 2009b). Resource selection based on minimal time since fire can be observed in northern ungulates, particularly during the winter, when forage is limited (Seip & Bunnell 1984, 1985; Peck & Currie 1992). The limiting factor for species such as Stone's sheep (*Ovis dalli stonei*) is winter access to forage. Access and availability of winter forage may be associated with minimal time since fire (Seip & Bunnell 1984). Predator movements and resource selection may be influenced by prey movements and their resource selection (Walker et al. 2006). Therefore, although there may be general resource requirements, they may shift in specific areas depending on predator–prey interactions. Distribution of species may also depend on weather, precipitation events, population size, abundance of resources, and human interactions. Whether a species is a specialist or a generalist and what limitations are imposed by the environment should be a central consideration in landscape-level management, along with the different reproductive cycles and requirements of each species (Hatler & Beal 2010). Depending on the season and the climatic variations, there may be stronger selection for areas with minimal time since fire, especially by ungulates, including Stone's sheep, elk (*Cervus elaphus*), and moose *(Alces alces andersoni*). Snow-free open rangeland is essential for winter use by wildlife (Elliott 1983). Conversely, during the summer, adequate nutrition provided by open rangeland, driven by recent time since fire, is required to prevent reduction in conception, pregnancy rates, and calving, and to maintain proper nutrition for lactation (Couturier et al. 2009). Varied time since fire across the landscape can provide the nutritional requirements of ungulates (Elliott 1983; Allred et al. 2011).

Photo credit: S.E.R. Leverkus, 2009

Based on resource requirements of multiple species and how time-since-fire influences resource structure, pattern, and availability, a potential target distribution of time since fire across the landscape at regional and watershed scales is hypothesized (Table 5). The distribution was developed based on approximated percent ranges for time since fire as a baseline to use in further discussions with stakeholders and land managers. The division between time-since-fire classes is representative of the vegetation response to fire in the boreal forest where land cover classes shift through time. Burnable area represents vegetation (fuel) that is available for consumption by fire (i.e., grass, forbs, and woody plants versus rock and ice, which are currently considered unburnable). Given the percentages that have been hypothesized in each time-since-fire class, there would be a shift as each year passes. If the desired range of minimal time since fire (0–2 years) is 0–10% of the burnable area, 0–467 155 ha of the M-KMA would need to be burned by wildfire or prescribed fire, or a combination of both, annually until the targeted area of time since fire was reached (Table 5). Even in the watersheds of the M-KMA that have larger areas burned, most of the fire occurred more than 25–50 years ago (Table 2). In order to have a certain percentage of the land in more than 30 years since fire, in 30 years' time, there needs to be more area burned over the next current decade. Results show, however, that there has been a downward trend in prescribed fires over the past 29 years, with a maximum recorded historical size of only 6100 ha (Leverkus 2015). It is acknowledged that the data set has limitations due to remoteness and the complexity of recording fire across the region.

No analyses have yet been performed on the spatial or temporal distribution of time since fire across the M-KMA or on the requirements by the priority species for varying time since fire. Therefore, the spatial and temporal distribution of fire as constructed in this article serves as a first step in the development of a landscape disturbance matrix for the M-KMA, where vegetation structure and diversity are driven and maintained by varying time since fire and accompanying ecological processes. To successfully follow management direction of spatial and temporal distribution of time since fire across the landscape, regardless of jurisdiction, continual fire is needed. It is suggested that the use of an LDM is warranted if there is a desire to conserve multiple species and biodiversity in the region. A series of LDMs for the M-KMA is presented, which can provide land managers with a tool to track fire across the landscape in order to reach biodiversity objectives and to ensure appropriate time since fire is spatially and temporally distributed across the landscape.

Applying the landscape disturbance matrix

Planning and management

Landscape disturbance matrices can be used to develop a plan for maintaining an appropriate amount of fire across the landscape. This produces sustained critical habitat for priority species through shifting mosaics and may reduce susceptibility to other disturbances, such as mountain pine beetle (*Dendroctonus ponderosae*) infestations. The combination of tree mortality from mountain pine beetle and long time interval since fire, together with a regional increase in lightning strikes and mean annual temperature, can result in unplanned, severe wildfires. Using the LDM as a model for landscape management and planning could avoid, mitigate, and/or prepare for ecosystem effects from such pest and disease outbreaks, natural disturbances, and other influences that could decimate a landscape of uniform structure, age, and quality.

Advantages of the landscape disturbance matrix

The LDM can account for and resolve years without disturbance (e.g., when fire was absent from the landscape), variable seasons, variable disturbance intensities, pattern design across the landscape through space and time, and successful development and achievement of objectives. The LDM can be continually updated by incorporating the spatial distribution of fire using Landsat imagery, current fire data derived from government agencies, or tools such as LANDFIRE (Brockett et al. 2001). Main annual or monthly updates to the LDM will be conducted based on spatial analysis of area burned and area desired to be burned. The following months' or year's plans can be altered as disturbances occur or do not occur across the landscape or as management objectives shift.

Additional variables

Additional variables to consider when developing LDMs and implementing fire plans on the landscape include weather and fuel conditions, variable seasons, variable fire intensities, and variable numbers of fires. All types of ignition sources on the landscape need to be considered (i.e., lightning and anthropogenic, including industrial ignitions), as well as a contingency plan for years with no fire due to unforeseen circumstances. This may occur if prescribed fire permitting is not approved or the indices were inappropriate for meeting desired objectives. Whether or not specific patterns across the landscape are needed and how they shift through time would be of primary consideration for the land manager when using the LDM. Other features to consider when designing an LDM include presence or absence of species-specific required resources and vegetation cover. Limitations to the

LDM include patch size of fires and drought integration. There are other places where drought may play a more important role than in the boreal forest. Monitoring programs are required to ensure that objectives are being met and continual iterative feedback into the model is provided (van Wilgen 2013). Such a monitoring program could range from a simple geographic information system (GIS) exercise to rigorous and time-intensive inventorying, which is dependent on available resources and goals.

There may be areas across landscapes that need to be without fire, such as Old Growth Management Areas, just as there may be areas that can absorb or resist fire. Areas with longer time since fire may be needed for critical habitat of certain fur-bearing mammals, songbirds, or caribou. In the boreal forest, consideration must be given to permafrost, whereby continuous and discontinuous areas of permafrost should remain in long time-since-fire classes. These areas for permanent refugia from fire should be spatially documented and protected. Additionally, fire-absorbent and fire-resistant landscapes should be identified. Fire-absorbent landscapes are defined as landscapes that are characterized by fire-adapted and fire-maintained species. Fire-absorbent landscapes may have recent time since fire, and thereby provide a fuel break across a broad landscape. Fire-absorbent and disturbance-absorbent landscapes will be increasingly important as the duration, intensity, and distribution of fire and other disturbances increase globally. Fire-absorbent and fire-resistant landscapes will also continue to play an important resilience role across the landscape by withstanding the disturbance of fire.

Severe fire weather across the western Canadian boreal forest has been predicted, with increases in the proportion of the landscape burned by head fire and two peaks of fire occurrence through the year, which could result in an increased number of large fires (de Groot et al. 2013). Models developed for the boreal forest suggest an increase of 20–50% in annual area burned due to continued changing climate, which may reduce fire return intervals from potential upper levels of 150 years to 100 years in some locations (Kasischke et al. 1995). Effects on terrestrial carbon in the boreal forest resulting from an increase in fire severity and occurrence due to climate change, longer fire seasons, and more lightning activity have been predicted (Amiro et al. 2001; Stocks et al. 2003; Flannigan et al. 2009; Wotton et al. 2010). A higher percentage of deciduous trees in the boreal forest is anticipated to result from this shift in fire regime, which is also expected to increase carbon storage (Kasischke et al. 1995). Twenty-five percent of the global vegetation carbon pool is stored by boreal forests (88 petagrams of carbon) (Dixon et al. 1994). Natural disturbances along with vegetation age class structure, disturbance history, and woody debris influence carbon dynamics by acting as either carbon sources or sinks (Kurz & Apps 1999). The LDM provides a framework for strategically discussing and planning fire management in a changing climate while accounting for multiple landscape objectives and considerations.

Implications

The paradigm around management and conservation of biodiversity needs to shift to incorporate varying spatial and temporal scales (Fuhlendorf et al. 2012). Around the world, managers are slowly moving their focus from single species and large game promotion to broader biological diversity conservation (van Wilgen et al. 2007). Others have brought forward similar management planning across the world, but the LDM is well suited to be used both broadly at large scales and narrowly at smaller scales (Brockett et al. 2001; Schmiegelow et al. 2006; Haufler et al. 2008). The LDM can be modified so that the desired patterns across the landscape and heterogeneity objectives are achieved. The matrix can be altered to reduce prescribed fire in years when there is more wildfire than anticipated or to increase prescribed fire when there is a lack of wildfire, all of which influences heterogeneity and biodiversity. The way to conserve biodiversity is by a forward-thinking, ecologically, and culturally appropriate management approach based on past and current disturbance regimes (van Wilgen et al. 2007; Parr et al. 2009; Twidwell et al. 2013). Integrating historical data and knowledge about patterns and processes into current and future management will result in an ecologically and culturally appropriate approach to managing natural resources (Swetnam et al. 1999). Fire is only one type of disturbance that can be modelled using LDMs. Other disturbances used in LDMs could include drought, flood, natural resource development, and industrialization of landscapes.

There is no single disturbance regime for an entire landscape across a broad scale. There are requirements by species and by areas for varying disturbance frequencies and intensities. To conserve biodiversity, heterogeneity and shifting mosaics must be maintained. To achieve this, land managers need to view fire as an ecological process that drives ecosystems rather than as a tool to be used in certain locations or suppressed in others. The complexity of processes across landscapes must be managed appropriately. This new paradigm of management and conservation of biodiversity is supported in the recent literature. Schmiegelow et al. (2006) suggest that this form of natural disturbance-based management is particularly appropriate where disturbances, such as fire, occur across broad spatial and temporal scales. A solution is found in the design and use of the LDM as a landscape-level management plan and tool for the conservation of biodiversity, which models the main parameter of time since fire across the landscape. To maintain heterogeneity and biological diversity and provide resources for selection by wildlife, disturbances need to be spatially and temporally distributed across the landscape. A landscape disturbance matrix can be developed regardless of location or scale by following the four steps that have been proposed: (1) develop an inventory of recent disturbance history and ecosystem condition, (2) identify the historical range and variability of disturbance for each site, (3) determine landscape management objectives based on review and discussion, and (4) develop a desired landscape disturbance matrix to meet landscape management objectives.

Enabling critical disturbance processes such as fire can maintain diverse biological and ecological systems. This should be the central framework for managing natural resources in the face of socio-ecological uncertainties, such as those associated with climate change (Burton et al. 2008). Recognizing that the interaction of disturbances is a pattern-driving process that contributes to heterogeneity is of global significance for conserving biodiversity and cultures (Fuhlendorf et al. 2012). It is imperative for land managers to recognize that multiple fire frequencies and disturbance regimes have existed and will continue to fluctuate given a changing climate, and that time since fire that results in varied vegetation structure across the landscape is critical for many species and communities (Rowe & Scotter 1973; Strauss et al. 1989; Johnson et al. 1998; Burton 2008). The presence of fire-absorbent landscapes resulting from these shifting mosaics are growing more critical every year as catastrophic wildfire events become the norm, stretching earlier and later into the fire season. The landscape disturbance matrix is a tool that can provide support for the ecological resilience of a landscape to ensure that biodiversity is conserved into the future, because the future promises more disturbance, not less (Turner et al. 1993; Stocks et al. 1996; Volney & Hirsch 1996; Pyne 2007; Fuhlendorf et al. 2012; Bowman et al. 2013).

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