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Environmental drivers of large, infrequent wildfires: the emerging conceptual model

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Abstract: Large, infrequent fires (LIFs) can have substantial impacts on both ecosystems and the economy. To better understand LIFs and to better predict the effects of human management and climate change on their occurrence, we must first determine the factors that produce them. Here, we review local and regional literature investigating the drivers of LIFs. The emerging conceptual model proposes that ecosystems can be typified based on climatic conditions that determine both fuel moisture and fuel amount. The concept distinguishes three ecosystem types: (1) biomass-rich, rarely dry ecosystems where fuel moisture rather than fuel amount limits LIFs; (2) biomass-poor, at least seasonally dry ecosystems where fuel amount rather than fuel moisture limits LIFs; and (3) biomass-poor, rarely dry ecosystems where both fuel amount and fuel moisture limit the occurrence of LIFs. Our main goal in this paper is to discuss the drivers of LIFs and the three mentioned ecosystem types in a global context. Further, we will discuss the drivers that are not included within the 'fuels' versus 'climate' discussion. Finally, we will address the question: what kinds of additional information are needed if models predicting LIFs are to be coupled with global climate models? As with all generalizations, there are local deviations and modifications due to processes such as disturbance interaction or human impact. These processes tend to obscure the general patterns of the occurrence of LIFs and are likely to cause much of the observed controversy and confusion in the literature.

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Key words: biomass, climate, disturbance interaction, fire size, fire suppression, fire weather, fuel amount, fuel moisture.

I Introduction

Large, infrequent fires (LIFs) can have substantial impacts on both ecosystems and the economy (Viegas, 1998). In Indonesia, for example, fires burned 3.6 million ha of scrub and forest in 1982–83, causing economic losses of approximately US$9 billion (Kinnaird and O'Brien, 1998). In 1998, catastrophic wildfires had an estimated impact of 600–800 million US$ in northeastern Florida (Butry *et al*., 2001). Such events have increased the awareness of LIFs 'becoming more comparable to the risk from other natural perils' (American Re's Geoscience Department, 2003: 31).

LIFs have effects on ecosystems that are out of proportion to their short duration; the imprint they leave is large in area and may persist for a very long time (Turner and Dale, 1998; Viegas, 1998; White and Jentsch, 2001; Figure 1). For example, in the tropical rain forests LIFs may eliminate thousands of species (eg, ground-dwelling organisms with limited ranges); thus the extensive fires in Brazil and Indonesia in the 1980s and 1990s might be among the largest biological selection events in modern history (Ginsberg, 1998; Kinnaird and O'Brien, 1998). However, one should be careful when equating LIFs with ecological catastrophes. Following the 1988 Yellowstone fires, for example, plant cover and composition recovered by natural processes relatively quickly and no extirpations occurred (Romme and Turner, 2004). Turner *et al*. (2003) concluded that LIFs may play a key role for population structure, genetics and evolution of long-lived clonal plant species, and are an important source of landscape heterogeneity. The need of fire, including LIFs, to maintain the health of fire-adapted forests was also emphasized by Moritz and Odion (2004).

In spite of their ecological and economic importance, the factors allowing for the formation of LIFs are not well understood (Turner and Dale, 1998). The discussion on the preconditions for large wildfires is especially controversial in North America in the context of fire suppression and fuel management (eg, Minnich and Chou, 1997; Keeley *et al*., 1999; Keeley and Fotheringham, 2001a; 2001b; Minnich, 2001; Moritz, 2003; Turner *et al*., 2003; Moritz *et al*., 2004; Schoennagel *et al*., 2004; Stephens and Ruth, 2005). This discussion is based on two contrasting concepts. The first (a) implies that fuel is crucial and that fire suppression has led to an increase in fuel load and continuity causing larger and more severe fires. Therefore, prescribed burning and other fuel manipulations are considered an adequate tool in reducing fire risk. The second concept (b) implies that fire suppression has not had any effect on fire size because fire weather (fuel moisture) is the critical factor allowing for LIFs. Therefore, prescribed burning is not considered to reduce the risk of LIFs and may even have negative ecological impacts due to increased fire frequency in ecosystems that normally experience infrequent fires. Concept (a) was developed based on observations in open *Pinus ponderosa* forests in SW USA (Mutch *et al*., 1993; Arno *et al*., 1995; Covington *et al*., 1997; Fulé *et al*., 1997) while concept (b) originates from observations in the subalpine forests of the Canadian Rocky Mountains (Johnson and Wowchuk, 1993; Bessie and Johnson, 1995).

Motivated by concept (a), prescribed burning has been applied uncritically to different ecosystem types in order to reduce the risk of LIFs (Johnson *et al*., 2001; Keeley and Fotheringham, 2001b). But recently some authors have argued that a more differentiated view is necessary for ecological reasons, to be able to reduce the risk to life and economic values and in order to limit the large expense of prescribed burning (Gutsell *et al*., 2001; Johnson *et al*., 2001; Keeley and Fotheringham, 2001b; Veblen, 2003;

Figure 1 Impact of a large, infrequent fire in Colorado. This photograph was taken by Michael Menefee in 2003, one year after the Hayman fire. The Hayman fire was caused by arson. It burned from 8 June till 2 July 2002, was the largest wildfire (*c*. 558 km^2) ever recorded in Colorado and cost approximately US$39.9 million to suppress. The photograph shows an area that got burned by high intensity – virtually all trees were killed. However, even the largest fires do not burn the whole area within their fire perimeter with high intensity but rather in a mosaic pattern. Thus almost half of the area within the perimeter of the Hayman fire either did not burn, or burned with low intensity
Source: Michael Menefee (2006).

Schoennagel *et al*., 2004). Thus, knowing the relative importance of the factors that cause LIFs is essential.

Numerous authors have investigated the role of either fuel or climate for the formation of large wildfires in ecosystems worldwide on different spatial and temporal scales. These studies describe two major systems: first, biomass-rich, rarely dry ecosystems where large, infrequent fires (LIFs) are limited by climate and second, biomass-poor, at least seasonally dry ecosystems where LIFs are limited by fuels. However, these studies do not attempt to place the respective systems in a global framework. Our main goal in this paper is to discuss the drivers of LIFs in a global context and to present a global framework. Further, we will discuss the drivers that are not included within the 'fuels' versus 'climate' discussion. Finally, we will address the question: what kinds of additional information are needed if models predicting LIFs are to be coupled with global climate models?

1 LIFs: definition

Following Turner *et al*. (1998) and Turner and Dale (1998), we define large, infrequent fires (LIFs) as fires exceptional in their large spatial size (Figure 2) relative to the fires that usually affect the respective ecosystem. These usually occur infrequently (Turner *et al*., 1998). In addition, in our literature review we assumed that both 'years with large annual area burned' and 'years of widespread fire' are related to LIFs. Although they only represent a small number of all fires, they usually account for the largest part of annual area burned (Vázquez and Moreno, 1995; Grau, 2001; Skinner *et al*., 2002). Thus, years with a large area burned generally represent years with

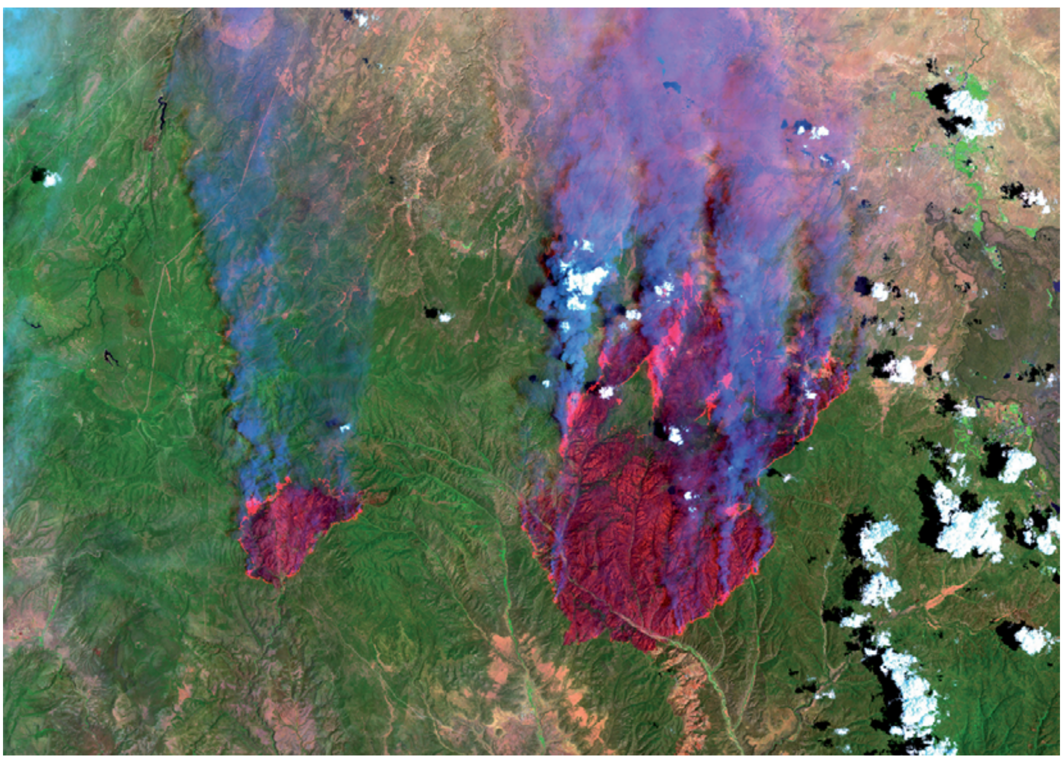

Figure 2 Large, infrequent fire in Arizona. The image shows the Rodeo fire (right) and Chedinski fire (left) on 21 June 2002. The two fires, which were started by arson by a lost hiker on 18 June, merged into a single large fire – the Rodeo-Chedinski Fire – over the course of two weeks and were not controlled until 7 July 2002. The Rodeo-Chedinski fire finally burned *c.* 1,890 km^2, costing more than US$30 million before it was contained. It was the largest and most expensive fire in Arizona's known history. The image was taken from the Landsat Enhanced Thematic Mapper Plus (ETM+) on 21 June 2002
Source: NASA/USGS (2002).

large fire events, as has been shown for northern Patagonia, the United States (Kitzberger *et al*., 2001), Canada (Stocks *et al*., 2002), central Australia (Griffin *et al*., 1990), Spain (Moreno *et al*., 1998), Portugal (Viegas, 1998) and California (Moritz, 1997). By considering both 'years with large annual area burned' and 'years of widespread fire', we acknowledge that climate can synchronize fire events on regional scales during one year (Veblen *et al*., 2003); eg, the Sydney bush fire in January 2002 (Reuters Ltd, 2002), or the 1997 fires in Indonesia (Kinnaird and O'Brien, 1998). Economically, regional synchronization of fire is relevant because it stretches management resources thinly, and because current fire fighting technology cannot cope successfully with multiple fire events (Fernandes and Botelho, 2003). The term 'wildfire' or 'fire' refers to uncontrolled fires. These often occur in wildland areas but can also consume buildings or agricultural resources. They can be natural or human induced.

In this review, we have not distinguished LIFs by fire intensity, although to burn as an LIF fires must achieve intensities sufficient for self-propagation of the fire across some variability in fuel or environmental conditions. For instance, in the ponderosa pine forests of southwestern North America, original structures under frequent fire regimes were savannas with abundant ground-level fine fuels (Covington, 2000). With fire suppression and succession, ingrowth in the understorey produces 'ladder fuels' which can carry fire into the canopy. In theory, both structures can support LIFs, but the savanna structure produces a lower-intensity fire than a stand with dense understorey trees. The latter had greater ecological impact.

II The emerging conceptual model for LIFs

The first and coarsest scale factors that control LIFs are 'climate' (sometimes referred to as a 'top-down' factor for the control of fire) and 'fuel' (sometimes referred to as a 'bottom-up' control because ecosystem conditions are paramount). We suggest that 'climate' and 'fuel' are the endpoints of a gradient that is determined by long-term (decadal) climatic conditions. Further, for clarity, this discussion should be viewed as 'fuel moisture' (rather than climate) versus 'fuel amount' because both fuel amount and fuel moisture are outcomes of climatic conditions.

Long-term climate influences both fuel amount and fuel moisture in an ecosystem (eg, Bond and van Wilgen, 1996; Grau and Veblen, 2000). It influences the amount of fuel (biomass) in ecosystems by influencing primary productivity and decomposition, as is obvious when considering the global distribution of biomass (Chapin *et al*., 2002). Long-term climate at a specific location also implies a characteristic frequency, extent and duration of fire weather and short-term (ie, seasonal to annual) climatic conditions, eg, drought or large-scale atmospheric circulation anomalies, such as the El Niño Southern Oscillation (ENSO). These mainly influence fuel by lowering the fuel moisture content, generally through increased temperature, low precipitation, wind and/or low relative humidity. Thus, long-term climate is the superordinate mechanism determining whether (1) fuel moisture, (2) fuel amount, or (3) the interaction of both limits extreme fire events. We therefore use this as the basis of our first approximation of a general conceptual model: that climatic patterns produce the observed gradient in the importance of fuel moisture versus fuel amount in the occurrence of LIFs. This model has been developed in the North American literature by Swetnam and Baisan (1996), Johnson *et al*. (2001), Schoennagel *et al*. (2004) and Gedalof *et al*. (2005).

Using this conceptual model, an arbitrary number of ecosystem types can be described along the gradient. However, in order to keep things simple we propose three types of ecosystems prone to LIFs (Figure 3), two of which (1 and 2 below) represent the extremes of the fuel moisture-fuel amount discussion from North America and one of which is new. These three types are: (1) biomass-rich, rarely dry ecosystems where fuel moisture rather than fuel amount limits LIFs; (2) biomass-poor, at least seasonally dry ecosystems, in which fuel amount, rather than fuel moisture limits LIFs; and (3) biomass-poor, rarely dry ecosystems, in which both fuel amount and fuel moisture are limiting, and LIFs occur in dry years following wet years with increased organic matter production. The ends of the fuel moisture–fuel amount gradient can also be used to describe the two extremes in which LIFs do not occur: biomass-rich, never dry ecosystems, in which fuels are never dry enough to burn (the wettest rain forests) and biomass-poor, always dry ecosystems, in which fuel is never continuous enough to carry a fire (sparse deserts).

In terrestrial ecosystems, certain combinations of fuel amount and fuel moisture never occur (Figure 3). Places that have abundant and continuous fuels cannot be 'always dry' because such dry conditions, in the extreme, would prevent biomass accumulation. Similarly, places that have sparse and non-continuous fuels cannot be 'never dry' because wet conditions would allow biomass to become continuous and abundant

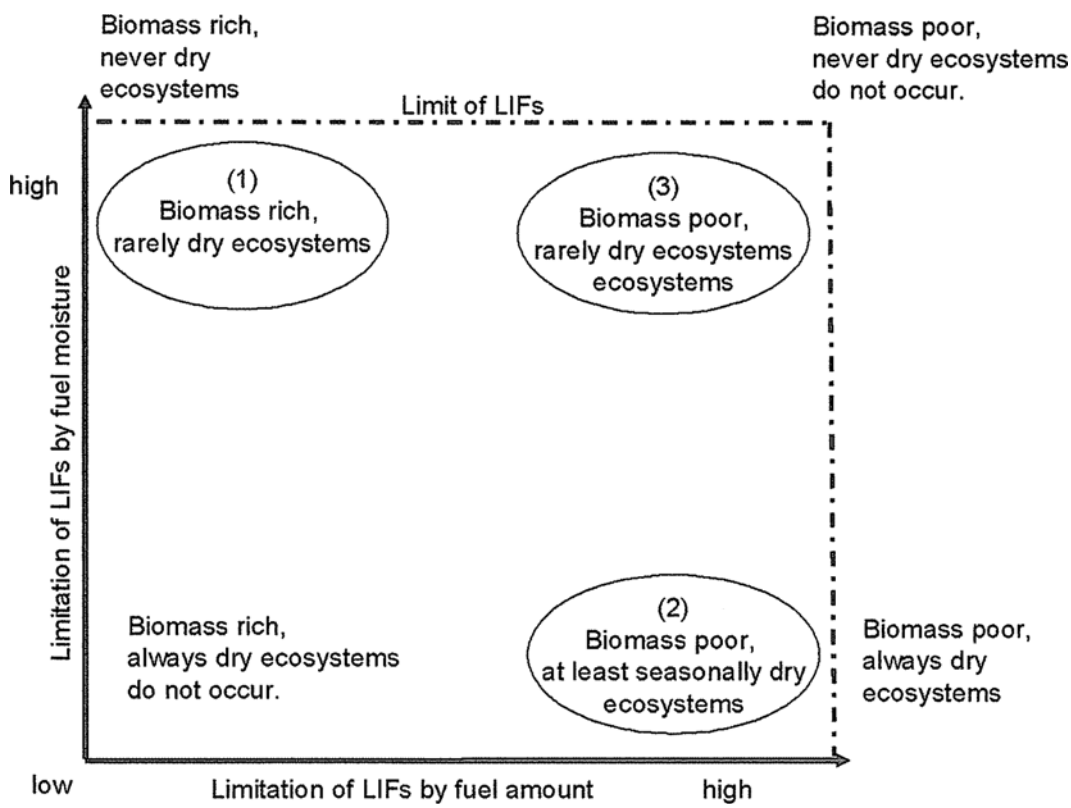

Figure 3 Schematic representation of how the relative importance of fuel moisture and fuel amount for the formation of large infrequent wildfires (LIFs) as determined by long-term climate varies depending on the type of ecosystem considered. The three circled ecosystem types are those that support LIFs (fires may occur outside the limits of LIFs but do not become LIFs in these ecosystems if their conditions remain constant). These three types are discussed more fully in the text and reviewed in Table 1

(though some deep sands and certain bedrocks may limit biomass production regardless of moisture availability). We also note that the combinations that lie outside the LIF box may, in fact, sometimes experience fire; it is just that these fires do not become LIFs (see Stott, 2000, and Ryan, 2002, for a general treatment of the fuel and environmental conditions for fire, of which the conditions for LIFs are a subset). Within the distribution of LIFs, conditions vary between three extremes:

(1) Biomass-rich, rarely dry ecosystems (due to long-term climate) in which fuel moisture rather than fuel amount limits LIFs. Here, the occurrence of an extreme drought or extreme fire weather (eg, strong dry and hot winds) is sufficient to allow LIFs to occur. Examples of this ecosystem type are temperate rain forests, subalpine forests, boreal forests and tropical rain forests (Table 1). Although in these ecosystems fuel structure and distribution might play a major role for fire behaviour under fire weather conditions that are not extreme, variation in fuel is relatively unimportant for the formation of LIFs as compared to fuel moisture.

(2) Biomass-poor, at least seasonally dry ecosystems, in which fuel amount rather than fuel moisture is limiting LIFs. This ecosystem type is generally situated in dry climatic regions, where fuel is either limited through low primary productivity or due to a combination of relatively low primary productivity and frequent small fires (eg, dry and fertile savannas, forest-steppe ecotones; Table 1). Fuel moisture usually is not a critical factor because, even during years of normal weather, fuels are thoroughly desiccated during the dry season.

(3) Biomass-poor, rarely dry ecosystems (due to long-term climate) where both fuel amount and fuel moisture limit the occurrence of LIFs. This type of biomass-poor ecosystem is often situated in climatic regions where fuels are not dry and continuous enough for the occurrence of LIFs in average years (eg, *Austrocedrus* woodlands, high-elevation *Pinus aristata* forests). Here, LIFs can occur only when dry years follow years of above-average moisture availability and thus increased primary productivity (Table 1).

On a secondary level, the three ecosystem types where LIFs occur can be modified through human impact or disturbance interactions. In our opinion, this has caused much confusion and has so far prevented the development of a general concept at global scales. This is especially the case for ecosystem types one and two, eg, fragmentation and windthrow in biomass-rich, rarely dry ecosystems (type one) can create suitable conditions for a subsequent large, infrequent fire by indirectly lowering fuel moisture content over large areas.

Not all factors that control LIFs can be subsumed in the categories used in the first approximation conceptual model ('fuel amount' and 'fuel moisture'). A fuller model must include microclimate, fuel characteristics, and variability (including seasonality and interannual variation) in climate. For example, Swetnam and Baisan (1996) suggest that 'a combination of micro-environmental and fuel characteristics' is decisive for the contribution of fuel versus climate to LIFs in the low elevation *Pinus ponderosa* dominated forests to higher-elevation mixed conifer forests in the southwestern United States (Arizona, New Mexico, Texas and Sonora Mexico). Similarly, Schoennagel *et al*. (2004) point out that in the low-elevation *Pinus ponderosa* dominated forests to subalpine forests across the Rocky Mountains fuel characteristics determine whether climate or fuels play the key role. In addition, they point to the role of fire weather frequency (Schoennagel *et al*., 2004). The role of ecological characteristics of forests (eg, fuel structure and microclimate) in modifying the impact of climate is also proposed by Gedalof *et al*. (2005) for the dry to mesic forests in the American Northwest (Washington, Oregon and Idaho). Concerning the relative importance

Table – 1 Relative importance of fuel moisture versus fuel amount for the formation of large, infrequent fires (LIFs) in various vegetation types. Only a sample of the references cited in this paper is presented in order to illustrate the three ecosystem types of our general conceptual model. The detail of information given in the table varies according to the information provided by the corresponding authors. Note that Mediterranean-type ecosystems (eg, chaparral-dominated shrubland; grasslands and coastal sage scrub) are not all classified as pertaining to the same type. In areas with very steep climatic gradients, like in Mediterranean regions, fundamentally different systems can be found in close neighbourhood. In such areas, studies with different spatial resolution or different location may come to contradictory results

Vegetation type	Region	Weather in fire season/ fire year	Weather in years/season preceding large fire years	Remarks	Authors
Type 1 – Biomass-rich, rarely dry. Fuel moisture rather than fuel amount limits the occurrence of large, infrequent fires					
Boreal forests	Canada	Extreme fire weather conditions			Stocks *et al*. (2002)
Subalpine coniferous forests in Yellowstone National Park	Northern Rocky Mountains, USA	Extreme fire weather conditions and drought			Turner *et al*. (2003)
Giant sequoia (*Sequoiadendron giganteum* (Lindl.) J.) groves	Mid-elevations (1800–2300 m) on the western slope of the Sierra Nevada, California (USA)	Dry years		Synchronous occurrence of fire events in dry years	Swetnam (1993)
Mesic, dense, low-elevation forest types	Northern Rocky Mts (Idaho/Montana)	Regional April–October drought		Extensive fire years tended to be much drier in the northern (higher average precipitation) than in the southern Rocky Mts	Rollins *et al*. (2002)
High-elevation forests (mixed conifer and spruce/fir potential vegetation types)	Southern Rocky Mts (New Mexico) of the United States				
Coastal temperate rain forests (mesic to wet highly productive forests dominated by Sitka spruce (*Picea*	American Northwest (Oregon, Washington, Idaho)	Prolonged blocking events (increased 500 hPa heights) associated with raising temperatures and	Severe drought in the seasons preceding the fire season		Gedalof *et al*. 2005)

sitchensis (Bong.) Carrière) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.)		reduced relative humidity and with anomalous extremely dry and warm easterly foehn or chinook winds			
Pinus ponderosa Douglas ex C. Lawson, *Pinus strobiformis* Engelmann, *Pseudotsuga menziessii* Mirb. forests	Arizona, New Mexico, west Texas, northern Mexico (15 sites)	Deficient spring precipitation, high-SO phase		Synchronous large fires over three centuries associated with the high-SO phase, deficient spring precipitation, and reduced tree growth	Swetnam and Betancourt (1990)
Higher-elevation mixed-conifer forests	Southwestern USA (Arizona, Texas, New Mexico, Sonora Mexico)	Extreme drought years		No consistent lagging relations between large fire years and climate in preceding years	Swetnam and Baisan (1996)
Subalpine forests (Patchy forests and woodlands in the highest elevations of forests cover)	Colorado Front Range	Drought (often due to La Niña)	Weak tendency for above moisture conditions 3–5 years prior to fire occurrence	Less dependent on increased fuel production than fire occurrence at lower-elevation sites	Sherriff et al. (2001)
Subalpine forests	Front Range and Main Range of the Canadian Rocky Mts	Above-average temperature and below-average precipitation during the entire summer allowing for extreme drying of fuels		Weather is more important than differences in elevation and fuel variation associated with vegetation composition and stand age	Fryer and Johnson (1988); Johnson and Wowchuk (1993); Bessie and Johnson (1995)
Pinus ponderosa-dominated forests	Eastern Oregon and Washington	Dry, El Niño years (in one watershed, large fires also in wet year (La Niña year)	No influence	Local factors can override regional climate controls in some locations	Heyerdahl *et al*. (2002)
Nothofagus rain forests	Northern Patagonia	Extreme drought in spring and summer of the fire year (late stage of La Niña)	Fires less strongly favoured by drought in the previous spring of the previous year		Kitzberger *et al*. (1997)

(*Continued*)

Table 1 *(Continued)*

Vegetation type	Region	Weather in fire season/ fire year	Weather in years/season preceding large fire years	Remarks	Authors
Rain forests in the humid tropics	East Kalimantan, Borneo (Indonesia)	Prolonged droughts (El Niño)			Goldammer (1993); Ginsberg (1998)
Lowland rain forests	Sumatra, Kalimantan, Irian Jaya (Indonesia)	Drought (El Niño)		Poor logging practices, large-scale land clearing for agricultural projects and tree plantations predisposes forests to fire	Kinnaird and O'Brien (1998)
Tropical rain forests	Guinana	Severe drought (El Niño)		High-impact logging lowers fire-buffering capacity	Hammond and ter Steege (1998)
Tropical rain forests forests	Amazon basin of Brazil	Severe drought (El Niño)		Logging operations predispose forests to fire; severe drought provokes leaf shedding → increase dead fuel	Nepstad *et al*. (1998)
Amazonian moist evergreen forests (including relatively wet forests near Manaus, Amazonas)	Amazon basin of Brazil	Severe drought (El Niño)			Cochrane and Schulze (1998)
Fitzroya cupressoides rain forests	Northern Patagonia	Drought; warmer and drier spring-summer and springs		Fire years: late stages of La Niña; SE Pacific anticyclone more intense and located further south; absence of atmospheric blocking events at 50–60°S	Veblen *et al*. (1999)

Chaparral-dominated shrubland	California	Severe foehn winds (Santa Ana conditions) or extreme summer heat waves and low late winter and spring precipitation	No influence		Moritz (1997); Keeley *et al*. (1999); Keeley and Fotheringham (2001a); Moritz (2003); Moritz *et al*. (2004); Davis and Michaelsen (1995)
Hydric forest stands including *Taxodium distichum* (L.) Rich. (Bald cypress)	Northeastern Florida	Unusually severe drought; associated with El Niña			Mercer *et al.* (2000)
Coastal marshes, seasonal savannas, pine savannas, subtropical hardwood forests	Everglades National Park, Florida	Below-average dry-season rainfall (->) below-average dry-season surface water levels (during La Niña conditions)		Area burned and number of fires positively correlated with La Niña and negatively correlated with El Niño conditions	Beckage *et al*. (2003)
Type 2 – Biomass-poor, at least seasonally dry. Fuel amount rather than fuel moisture limits the occurrence of large, infrequent fires					
Dry vegetation types near the steppe ecotone	Northern Patagonia	Less dependent on drought because even 'normal' years are dry enough during the fire season	Above-average precipitation (El Niño)	Enhanced production of fine fuels prior to fire year	Kitzberger *et al*. (1997)
Grasslands	Northern Patagonia	Fire occurrence not significantly related to weather during fire year (summer drought is severe enough in average years)	Greater moisture availability in the spring of the year preceding fire seasons	Enhanced production of fine fuels prior to fire year	Veblen *et al*. (1999)
Grasslands	Intermountain West (USA)	No dominant pattern (moisture conditions in fire season are secondary to fine fuel amounts in controlling the occurrence of large fires)	Above-average in preceding summers	Sufficient fine fuel after wet summers	Knapp (1998)

(Continued)

Table 1 *(Continued)*

Vegetation type	Region	Weather in fire season/ fire year	Weather in years/season preceding large fire years	Remarks	Authors
Ecotones between Andean grasslands and montane forests (mosaic of grasslands, shrublands, forests in subtropical monsoonal climate)	Northwestern Argentina	Slight tendency for dry period in the five months preceding the fire season	Above-average moisture availability in the year preceding years of widespread fire	Enhanced production of fine fuels; impact of above-average moisture in year preceding fire season and of dry period directly preceding fire season depends on the site (dry, wet, intermediate)	Grau and Veblen (2000)
Grasslands and coastal sage scrub	Southern California and Baja California	Ordinary weather in summer	Above-average precipitation in previous winter	Enhanced production of fine fuels prior to fire year and increased stand continuity	Minnich (1983)
Perennial spinifex grassland and treeless plains to open woodlands	Central Australia	Wind speed is important	Two–three years cumulative antecedent rainfall	Increased production of native grasses	Griffin *et al*. (1983); Love and Downey (1986)
Dry savannas	Africa		Above-average rainfall in seasons preceding the dry season		Frost (1985)

Mixed conifer (*Pseudotsuga menziesii*, *Quercus gambelii* Nutt., *Pinus strobiformis*, *Abies concolor* (Gord. and Glend.) Lindl. ex Hildebr), or open *Pinus ponderosa* forest depending on aspect	Southwestern USA (Arizona)	Favourable burning conditions in early summer usually present even in average years	Greater moisture availability in the 1–2 years prior to a fire year	Enhanced production of fine fuels two years preceding the fire year in combination with limitation of potential fire spread leads to fuel accumulation	Baisan and Swetnam (1990)
Type 3 – Biomass poor, rarely dry. Both fuel amount and fuel moisture limit the occurrence of large, infrequent fires . These only occur in dry years following years/seasons of increased fuel production					
Austrocedrus woodlands	Northern Patagonia	Drought	Above-average moisture conditions during 1–2 growing seasons preceding the fire season	Enhanced production of fine fuels prior to fire year	Kitzberger and Veblen (1997
Xeric *Austrocedrus* woodlands	Northern Patagonia	Drought (late stages of La Niña; SE Pacific anticyclone more intense and located further south; absence of atmospheric blocking events at about 50–60°S)	Drier than average during the two preceding years; periods of greater moisture availability precede fire seasons by 3–5 years	Enhanced production of fine fuels 3–5 years prior to fire year	Veblen *et al*. (1999)
High-elevation *Pinus aristata* and low-elevation *Pinus ponderosa* forests (fairly uniform, thick, grassy understorey; low-density, open canopy stands)	Central Colorado	Drought (La Niña)	Greater moisture availability in the 2–4 years (El Niño) prior to a fire year; one year prior: reduced spring precipitation (La Niña)	Enhanced production of fine fuels prior to fire year	Donnegan *et al*. (2001)

(*Continued*)

Table 1 (*Continued*)

Vegetation type	Region	Weather in fire season/ fire year	Weather in years/season preceding large fire years	Remarks	Authors
Low- to high-elevation *Pinus ponderosa* forests	(Northern) Colorado Front Range	Spring or summer drought (El Niña)	Greater moisture availability in the 1–4 years prior to a fire year (El Niño)	Enhanced production of fine fuels prior to fire year	Veblen *et al*. (2000); Sherriff *et al*. (2001)
Pinus ponderosa dominated forests	Southwestern USA (Arizona, Texas, New Mexico, Sonora Mexico)	Very dry years	Very wet second and third year preceding the large fire year	Enhanced production of fine fuels prior to fire year	Swetnam and Baisan (1996)
Mediterranean ecosystems	Eastern Iberian Peninsula (Mediterranean Basin)	Dry summers	Above-average rainfall two years prior to fire year	Enhanced production of fuels two years prior to fire year	Pausas (2004)
Mediterranean-type ecosystems	Portugal	Extreme meteorological conditions	Total annual area burned increases with amount of rainfall during the winter-spring season up to a certain threshold	Growth of fine fuels	Viegas and Viegas (1994); Viegas (1998)

Table 2 Examples of how climate can influence fuel moisture and thus fire (various timescales)

Fire parameter and related climate parameter	Study area	Authors
Annual timescale		
Annual area burned from 1905 to 1990 varied with an index of the intensity of the Southern Oscillation (SOI); see also Figure 4	American Southwest	Swetnam and Betancourt (1990)
Annual area burned fluctuates significantly from year to year, primarily driven by the frequency and geographical extent of extreme fire weather/danger conditions	Canada	Stocks *et al*. (2001)
Direct association between extreme warm and cold phases of ENSO and fire danger; relationship being strongest in southeast and central Australia	Australia	Williams and Karoly (1999)
Large numbers of monthly acres burned in January through May are related to periods of below mean sea surface temperature (SST) in the central and eastern Pacific (El Niña conditions) causing below-average precipitation in Florida	Florida	Brenner (1991)
15 of the 17 largest fire years (1940–98) occurred during or just after El Niño episodes due to slightly warmer but significantly drier winter conditions in the Alaska interior and increased lightning activity in summer	Alaska	Hess *et al*. (2001)
Large Sydney wildfires of January 2004 occurred after a very dry year 1993, and in association with strong, dry winds	Sydney region, Australia	Speer *et al*. (1996)
Link between circulation anomalies in the mid-troposphere and large-fire years	Canada, American Northwest (Oregon, Washington, Idaho)	Skinner *et al*. (1999; 2002); Gedalof *et al*. (2005)
Seasonal and shorter timescales		
Association between extreme fire danger and dry, turbulent winds or foehn type winds such as the 'Mistral' in Southern France and the 'Tramontana' in Northern Italy	Mediterranean region	Viegas (1998)
Association between extreme fire hazard and extremely warm, dry easterly coastal 'foehn' and 'chinook' winds	American Northwest	Gedalof *et al*. (2005)
Years with persistent high-pressure systems exhibited larger fires, higher fire intensities and rates of spread than other years due to above-average temperature and below-average precipitation allowing for extreme fuel drying	Subalpine forests of the Rocky Mts	Johnson and Wowchuk (1993)
Most large fires occurred in years with an increased number of days with extreme fire weather conditions	Subalpine forests of the Rocky Mts	Bessie and Johnson (1995)
Large-fire events correspond with seasonal climate patterns at regional scales	Northern and Southern Rocky Mts, USA	Rollins *et al*. (2001)
Association between synoptic-scale weather patterns and extreme fire weather situations	Northern Territory of Australia	Tapper *et al*. (1993)

of climate versus fuel for LIFs in the boreal and subalpine forests in North America, Johnson *et al*. (2001) highlight the strength of variation in those two parameters as being decisive. They suggest that weather variation among fire seasons is more decisive than fuel variation with stand age because fuel moisture varies more widely than fuel load (Johnson *et al*., 2001). One of the attractions of the emerging general conceptual model is the potential for the variables, both derived from climate, to be coupled with climate change models in order to predict changes in the incidence of LIFs. Throughout our review we will discuss additional kinds of information that are needed if we are to predict LIFs from climate change models. After having introduced the three ecosystem types in which LIFs occur, we now review scientific evidence promoting the model with a special emphasis on adding international examples to the general framework emerging in North America.

1 Ecosystem type 1: fuel moisture as the limiting factor for large, infrequent fires (LIFs) in biomass-rich ecosystems

In biomass-rich ecosystems fuel amount is usually not limiting LIFs. Additionally, short-term climatic conditions favourable for burning (eg, prolonged droughts or extreme fire weather conditions) only occur rarely. Thus, in these ecosystems, fuel moisture is limiting LIFs. This has been shown by many studies investigating fire–short-term climate relationships in various ecosystems and regions of the world (see Tables 1 and 2; Figure 4).

Climate anomalies such as El Niño and associated prolonged droughts can allow for LIFs even in the humid tropics (Goldammer, 1993; Ginsberg, 1998; Nepstad *et al*., 1999; Stott, 2000). This is hypothesized to have been the case several times during the past 6000 years in the Upper Rio Negro region, Amazonia (Sanford *et al*., 1985; Meggars, 1994), and during the past 2200 years in Guiana (Hammond and ter Steege, 1998).

A link between circulation anomalies in the mid-troposphere and large-fire years has been proposed for subalpine forests of the southern Canadian Rocky Mountains (Johnson and Wowchuk, 1993). Years with persistent high-pressure systems exhibited larger fires, higher fire intensities and rates of spread than other years due to above-average temperatures and below-average precipitation, allowing for extreme fuel drying (Johnson and Wowchuk, 1993).

On a secondary level, the long-term climatic effect on fuel moisture in biomass-rich ecosystems can be modified and sometimes even overridden through disturbance interaction. The interaction of various types of disturbances such as fragmentation, insect pests, windthrow and frost can create suitable conditions for a subsequent large, infrequent fire by indirectly lowering fuel moisture content over large areas. In biomass-rich ecosystems, fire risk and size can be increased by fragmentation, as has been shown for tropical rain

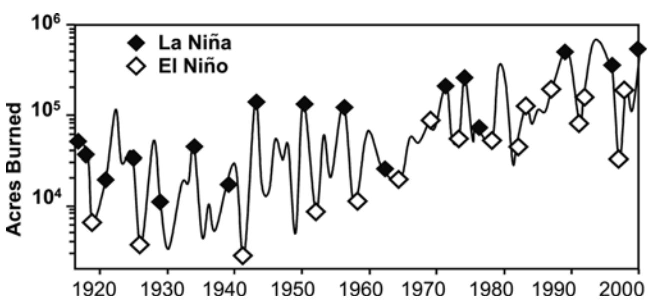

Figure 4 Relationship between El Niño and La Niña events and area burned in all federal state and private lands in Arizona and New Mexico (1905–94). Note the logarithmic scale on the y-axis

forests in the Amazon basin (Cochrane, 2001; Cochrane and Laurance, 2002). Here, fragmentation changes the understorey humidity of a stand by increasing wind speed and the amount of direct sunlight on the forest floor, allowing for the heating and desiccation of surface fuels (Nepstad *et al*., 1998). Likewise selective logging over large areas predisposes tropical rain forest to large forest fires (Uhl and Buschbacher, 1985; Ginsberg, 1998; Nepstad *et al*., 1998; Cochrane *et al*., 1999; Stott, 2000). Insect-caused tree mortality can increase the likelihood and severity of subsequent forest fire (McCullough *et al*., 1998; Fleming *et al*., 2002; Hummel and Agee, 2003). This has been discussed for subalpine (Baker and Veblen, 1990), subboreal (McCullough, 2000) and boreal forests (Fleming *et al*. 2002) in Northern America. Frosts in non-adapted ecosystems, eg, in the cerrado (savannas) of Brazil (Coutinho, 1990) or large-scale windthrow through hurricanes (Myers and van Lear, 1998), can increase the fuel availability by killing living plant biomass. Following Hurricane Hugo in South Carolina in 1989, the risk of uncontrollable, catastrophic wildfires was quickly recognized (Haymond *et al*., 1996).

To sum up, long-term climate is the superordinate mechanism of action determining that LIFs in biomass-rich, rarely dry ecosystems are usually limited by fuel moisture and thus only occur under extreme fire weather. However, on a secondary level, disturbance interaction may allow for LIFs under less extreme fire weather by lowering the fuel moisture content.

2 Ecosystem type 2: fuel amount as the limiting factor for large, infrequent fires (LIFs) in biomass-poor and at least seasonally dry ecosystems

Fires, which spread contagiously through a landscape, are critically dependent on the nature of the ecosystems through which they spread (Minnich, 1983; Walker, 1985; Turner *et al*., 1989). In biomass-poor, at least seasonally dry ecosystems, LIFs are usually constrained by the amount and continuity of fuels rather than by fuel moisture status, because even during years of normal weather, fuels are well desiccated during the dry season (Kitzberger *et al*., 1997; Veblen *et al*., 1999). In this ecosystem type, fuel is limited either through low primary productivity or due to a combination of relatively low primary productivity and frequent small fires or removal of fuels through other disturbances such as grazing.

The relevance of fuel bed continuity and fuel amount for fire size has been observed in semi-arid *Pinus ponderosa* forests and Piñon-Oak juniper woodlands (*Pinus edulus* Engelmann, *Juniperus deppeana* Steud., *J. monosperma* Engelmann, and *Quercus* spp.) of the southwestern United States (Rollins *et al*., 2002) and the Sonoran Desert (Rogers and Vint, 1987). This has also been reported from anthropogenically modified landscapes such as the longleaf pine savannas of the southeastern United States (Frost, 1993) and the savannas of South Africa (Manry and Knight, 1986), where habitat fragmentation has produced smaller fire compartment sizes. For a discussion of the relevance of fuel continuity for fire propagation in the context of prescribed burning, see Fernandes and Botelho (2003).

An increase in biomass due to above-average moisture availability in the season or years preceding LIFs has been found to be a usual prerequisite for LIFs in dry savannas of Africa (Frost, 1985), xeric *Austrocedrus* woodlands (Kitzberger *et al*., 1997) and grasslands (Veblen *et al*., 1999) of northern Patagonia, as well as grasslands in the Intermountain West USA (Knapp, 1998), and grasslands and coastal sage scrub in Southern and Baja California (Minnich, 1983; see Table 1).

The influence of disturbance interaction or human impact on fuel amount can become a crucial factor under the general conditions of biomass limitation in at least seasonally dry ecosystems. Evidence for fuel effects in biomass-poor ecosystems includes: (1) fire suppression enhancing fuel buildup and fuel continuity; (2) prescribed burning removing fuel and fuel continuity; (3) land-use history and past disturbances affecting fuel amount and continuity;

Table 3 Examples illustrating the modification of the amount of biomass in an ecosystem through disturbance interaction and/or human impact

Ecosystem type or region		Authors
Increase in fuel amount due to fire suppression		
Pinus ponderosa forests of western North America	Effective fire suppression has led to unprecedented increases in stand densities and fuel accumulations	Mutch *et al*. (1993); Covington and Moore (1994); Arno *et al*. (1995); Swetnam and Baisan (1996); Covington *et al* (1997); Fulé *et al*. (1997); Keeley and Fotheringham (2001b); Fernandes and Botelho (2003)
Fire protected areas of the cerrado (savannas) of Brazil	Effective fire suppression has led to unprecedented increases in stand densities and fuel accumulations	Mistry (1998)
Increase in fuel continuity and/or load due to changes in land use, land-use history and past disturbances		
Around Patagonian coastal cities	Abandonment of ranches and associated lack of grazing has permitted recovery of vegetation and accumulation of fine and medium-sized dead fuels	Dentoni *et al*. (2001)
Ecosystems where herbaceous material represents the major part of the fuel load; eg, a) arid savannas, b) floodplains of Kakadu National Park in monsoonal northern Australia	Removal of herbivores has led to increased fuel loads and thus to increased burning and larger fire sizes	a) Walker (1985); van Wilgen and Scholes (1997) b) Russell-Smith *et al*. (1997)
Large parts of the montane zone of the Colorado Front Range	Today's forest structure (extensive, roughly similar aged post fire stands) is the legacy of widespread, stand-replacing fire in the mid-nineteenth century due to both Euro-American settlement and increased climatic variability	Hadley and Veblen (1993); Veblen *et al*. (2000)
Nothofagus-Austrocedrus forests in Northern Patagonia	Extensive burning of mesic forests in the 1890s to 1920s resulted in vast areas of even-aged stands	Veblen *et al*. (1999)
Central Spain	Tendency of fires to homogenize landscapes even when burning different vegetation types	Pérez *et al*. (2003)

and (4) fuel removal through disturbance interaction, for example through avalanches or grazing. These arguments associate the occurrence of LIFs with temporal fuel succession and accumulation in relation to fire return period, or with spatial fuel continuity in relation to fire spread.

In some ecosystems, humans have lengthened fire-free intervals by suppressing natural fires to protect resources and human lives. This may alter fuel conditions and can lead to increased fire intensity and fire spread due to reduced landscape heterogeneity and increased fuel loads (Agee, 1993; Covington and Moore, 1994; Mistry, 1998; Covington, 2000; Keeley and Fotheringham, 2001b; see Table 3), as has been observed mainly in ecosystems that formerly were characterized by frequent surface fires such as the *Pinus ponderosa* forests in the southwestern USA, northwestern Durango, Mexico (Fulé *et al*., 1997), the forest-grassland ecotones in the Patagonian *Austrocedrus* woodlands-steppe (Veblen *et al*., 1992), the ponderosa-pine-forest-grassland boundary in the Colorado Front Range, USA (Mast *et al*., 1997), and the cerrado (savannas) of Brazil (Mistry, 1998).

As opposed to fire exclusion, prescribed burning has been shown to be an effective tool to prevent the occurrence of large wildfires by limiting fuel buildup in some ecosystems, such as in the cerrado (savannas) of Brazil (Mistry, 1998), in the African savannas (Walker, 1985), in the open forest/woodland type of monsoonal northern Australia (Russell-Smith *et al*., 1997), and in mixed-conifer ecosystems of Yosemite National Park (Stephens, 1998) and the Sierra Nevada of California (van Wagtendonk, 1996). However, the duration of the effect of prescribed burning on the probability of large wildfires depends among others on the intensity and spatial configuration of the prescribed burn, the fuel type and on the primary production of the ecosystem influencing the fuel reaccumulation rate (Minnich, 1998; Fernandes and Botelho, 2003).

Land-use history and the history of past disturbances can alter the frequency and magnitude of current disturbances (Baker, 1995; White and Jentsch, 2001) by influencing vegetation structure, and thus fuel continuity and fuel load (see Table 3). For example, in the northern Mediterranean Basin, 'underutilization of species' due to rural depopulation led to an increase of insect pests due to vast areas of even-aged stands and the accumulation of litter, thus allowing for large wildfires (Barbero *et al*., 1990). In the spinifex grasslands of central Australia, the cessation of traditional aboriginal burning practices, which formerly increased landscape heterogeneity and reduced fuel loads, has allowed for the occurrence of LIFs (Allan and Baker, 1990; Griffin *et al*., 1990). In other ecosystems, extensive burning during certain historical periods has left a legacy of dense, even-aged stands over large areas that today represent a hazardous fuel source increasing the potential for catastrophic fires (Veblen *et al*., 2000; see Table 3).

Disturbance interaction can mean that one disturbance delays or limits another due to fuel removal. In the Colorado Rocky Mountains, Veblen and others found that in subalpine forests avalanche scars limited fire size by restricting fire spread (Veblen *et al*., 1994). In Wyoming, Romme (1982; see also Romme and Knight, 1981; Romme and Despain, 1989) showed that high-intensity fires were spaced by centuries because they burn fuels that take centuries to reaccumulate.

In some ecosystems, grazing reduces fuel and thus fire spread and size. For example, this has been reported for herbivore consumption in the arid and fertile savanna systems of southern Africa (Walker, 1985; van Wilgen and Scholes, 1997) as well as for livestock grazing in the coastal sage scrub vegetation of Baja California (Minnich, 1998) and for dry pine-oak forests and grasslands in Durango, Mexico (Fulé and Covington, 1999).

To sum up, long-term climate is the superordinate mechanism of action determining that in biomass-poor, at least seasonally dry ecosystems LIFs are usually limited by fuel amount. Therefore, secondary processes such as human impact and disturbance interaction may lead to LIFs due to fuel buildup and fuel continuity.

3 Ecosystem type 3: fuel amount and fuel moisture as limiting factors for large, infrequent fires (LIFs) in biomass-poor, rarely dry ecosystems

In some ecosystems only a combination of short-term climatic impacts on fuel amount and fuel moisture over periods of several years allows for the occurrence of LIFs (Table 1; see, for example, Veblen *et al*., 1999; Donnegan *et al*., 2001). This is the case in biomass-poor ecosystems, where average years are not dry enough to allow for large wildfires (Table 1). Both fuel and climate limit LIFs in these ecosystems.

Examples are high-elevation *Pinus aristata* forests and low-elevation *Pinus ponderosa* forests in central Colorado (Donnegan *et al*., 2001), the northern Colorado Front Range (Veblen *et al*., 2000) and southwestern USA (Arizona, Texas, New Mexico, Sonora Mexico; Swetnam and Baisan, 1996). Other evidence comes from Mediterranean-type ecosystems in Portugal where Viegas (1998) found that the total annual area burned increases with the amount of precipitation in the winter –spring season (up to a certain threshold) and is associated with extreme meteorological conditions. Similar findings are reported from the eastern Iberian Peninsula (Mediterranean Basin), where the areas burned were higher two years after summers of above-average rainfall and in dry summers (Pausas, 2004).

In the literature, we have not found any examples for processes such as human impact or disturbance interaction modifying the long-term climatic effect on both fuel amount and fuel moisture in ecosystems. However, one can imagine that these secondary processes could modify either fuel amount or fuel moisture in this ecosystem type as well.

III Discussion

We have proposed a simple conceptual model for LIFs in which climate patterns underlie the gradient from fuel moisture control to fuel amount control. We now elaborate on several complexities in the application of this model.

One potential problem occurs when the relative importance of fuel amount versus fuel moisture varies on multiple timescales. For example, fuel moisture may become unusually important in biomass-poor, at least seasonally dry ecosystems, when a series of wet years causes unusually high biomass production (Kitzberger *et al*., 2001). Decadal to even longer-term variation can be related to ENSO events or other long-term atmospheric circulation features (Villalba, 1994; Veblen *et al*., 1999; Daniels and Veblen, 2000; Hess *et al*., 2001; Kitzberger *et al*., 2001). And long-term temperature shifts on decadal- to centennial timescales can change the biomass status of an ecosystem, as has been reported for giant Sequioa groves in the southwestern USA (Swetnam, 1993).

Other uncertainties are introduced in the spatial domain, when local conditions override or modify regional climate controls (Swetnam, 1993; Heyerdahl *et al*., 2002; Gedalof *et al*., 2005). Factors such as topography may interact with fuel and fire weather and thus may change their relative importance. In areas with very steep climatic gradients, such as in Mediterranean regions (Bond *et al*., 2005), fundamentally different systems can be found in close neighbourhood. In such areas, studies with different spatial resolutions (scale effects) or different locations (zoning effects: Openshaw and Taylor, 1979) may come to contradictory results (Minnich, 1983; Viegas and Viegas, 1994; Davis and Michaelsen, 1995; Moritz, 1997; Viegas, 1998; Keeley *et al*., 1999; Keeley and Fotheringham, 2001a; Minnich, 2001; Moritz *et al*., 2004; Pausas, 2004; see Table 1).

A third factor that may obscure the relative importance of fuel moisture versus fuel amount is anthropogenic ignition. In some regions, such as today's subtropical and tropical savannas of Africa or tropical forests of India, fire size mostly depends on human manipulation (van Wilgen and Scholes, 1997; Stott 2000; van Wilgen *et al*., 2000). In some studies, direct ignition has even been considered as one of the major drivers for fire regimes (eg, for the Iberian Peninsula – Venevsky *et al.*, 2002; or many Mediterranean countries – Moreno *et al.*, 1998).

Fourth, the conceptual model only considers fuel moisture and fuel amount in an ecosystem as determined by long-term climate and does not consider variation in fuel structure, distribution or flammability. For example, this model does not take into account live–dead fuel ratios, large–fine fuel ratios or annual–total biomass ratios as Minnich (1998) does in his more detailed conceptual model for southern Californian chaparral, shrub and grasslands. The model also neglected variations of flammability of fuel – a parameter the importance of which has been pointed out to need further investigation by Venevsky *et al*. (2002) and Bond *et al*. (2005). In many ecosystems (eg, ponderosa pine under fire suppression), accumulation of fuel is accompanied by a radical change in fuel structure (Covington and Moore, 1994). With the development of so-called 'ladder fuels' (understorey trees in formerly savanna-like forests with abundant fine fuels along the forest floor), fires can carry into the flammable forest canopy.

Finally, we note that LIFs can reach intensities that cause fuels to dry quickly (Stott, 2000; Ryan, 2002). Thus, one way an LIF propagates is by influencing fuel moisture. A fire that begins under conditions suitable for an LIF in one location, can burn across stands that vary considerably in fuel amount and fuel moisture after it has reached a critical intensity (Johnson *et al*., 2001). Patterns of wind and weather can underlie the conversion of a non-LIF fire to an LIF (Ryan, 2002).

Nonetheless, reducing parameters influencing area burned to fuel amount and fuel moisture is attractive precisely because of its simplicity. The global fire model Glob-FIRM (Thonicke *et al*., 2001) has shown promising results for several sample regions in the world. This study relies on the same limiting parameters, fuel amount and fuel moisture. It also supports our hypothesis that the contribution of fuel amount and fuel moisture to LIFs varies with the biomass amount in an ecosystem as determined by long-term climate. Furthermore, the results of the Glob-FIRM model suggest that in some regions disturbance interaction (eg, grazing) and human impact (eg, fire suppression) render accurate area burned predictions difficult (Thonicke *et al*., 2001). This supports our reasoning concerning the impact of disturbance interaction and human impact on fuel amount in some areas, especially the biomass-poor ecosystems.

IV Conclusion

The emerging conceptual model proposes that ecosystems can be typified on a superordinate level based on long-term climatic conditions that determine both fuel moisture and fuel amount. The concept can be used to distinguish three ecosystem types as expressions of a gradient in the importance of fuel moisture versus fuel amount for LIFs: (1) biomass-rich, rarely dry ecosystems where fuel moisture rather than fuel amount limits LIFs; (2) biomass-poor, at least seasonally dry, ecosystems where fuel amount rather than fuel moisture limits LIFs; and (3) biomass-poor, rarely dry ecosystems where both fuel amount and fuel moisture limit the occurrence of LIFs. The two ends of the gradient are represented by two ecosystem types in which LIFs do not occur, biomass-rich, never dry ecosystems (wettest rain forests) and biomass-poor, always dry ecosystems (deserts). As with all extensive generalizations, there are local deviations and modifications due to processes such as disturbance interactions or human impact. In addition, fuel structure, flammability, variability in moisture, and self-promoting conditions created by fire itself play vital roles.

Knowledge of the factors limiting LIFs is crucial when it comes to predicting the consequences of direct human impact and global climate change. We hope that the emerging conceptual model will contribute to a better understanding of the observed patterns. Nonetheless, an empirical calibration of the model (precise analysis of biomass accumulation and fuel moisture versus environment) would increase the value of this approach to predicting changes in LIFs in the future. Further work should also examine global correlations between total environmental water supply (eg, from precipitation) and variability in water supply because correlations among these factors will influence how we map LIF risk. Incorporating fuel structure and flammability will be challenging because of the unique effects of individual species on these characteristics but is also an important area for continued research. These extensions would also allow us to parameterize the conceptual model proposed here to further assess its usefulness.

The proposed distinction of ecosystems has some management implications. In biomass-rich, rarely dry ecosystems (ecosystem type one), fire suppression is unlikely to have a major impact on fuel amount and fire size since fuel moisture and thus fire weather is the limiting factor. In this ecosystem type, climate change effects on fuel moisture are likely to influence fire sizes (eg, due to prolonged periods without precipitation, increase in summer temperature, stronger winds). In biomass-poor, at least seasonally dry ecosystems (ecosystem type two), fire suppression or removal of herbivores can lead to increased fuel loads and larger fires. On the other hand, prescribed burning might be an effective tool for reducing fire size. Here, climate change effects on fire size are related to parameters influencing primary productivity and decomposition and thus the amount of fuel. In biomass-poor, rarely dry ecosystems (ecosystem type three), fire suppression can lead to higher fuel loads, increasing the chance for large wildfires since only one more prerequisite – low fuel moisture – is necessary. Therefore, prescribed burning might be an effective tool to reduce fire size. In this ecosystem type, climate change effects on either fuel moisture or fuel amount (see above) or on both increase the likelihood for LIFs.

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