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ORIGINAL ARTICLE

Vulnerability of land systems to fire: Interactions among humans, climate, the atmosphere, and ecosystems

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Abstract Fires are critical elements in the Earth System, linking climate, humans, and vegetation. With 200–500 Mha burnt annually, fire disturbs a greater area over a wider variety of biomes than any other natural disturbance. Fire ignition, propagation, and impacts depend on the interactions among climate, vegetation structure, and land use on local to regional scales. Therefore, fires and their effects on terrestrial ecosystems are highly sensitive to global change. Fires can cause dramatic changes in the structure and functioning of ecosystems. They have significant impacts on the atmosphere and biogeochemical cycles. By contributing significantly to greenhouse gas (e.g., with the release of 1.7–4.1 Pg of carbon per year) and aerosol emissions, and modifying surface properties, they affect not only vegetation but also climate. Fires also modify the provision of a variety of ecosystem services such as carbon sequestration, soil fertility, grazing value, biodiversity, and tourism, and can hence trigger land use change. Fires must therefore be included in global and regional assessments of vulnerability to global change. Fundamental understanding of vulnerability of land systems to fire is required to advise management and policy.

Assessing regional vulnerabilities resulting from biophysical and human consequences of changed fire regimes under global change scenarios requires an integrated approach. Here we present a generic conceptual framework for such integrated, multidisciplinary studies. The framework is structured around three interacting (partially nested) subsystems whose

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dynamics contribute to vulnerability. The first subsystem describes the controls on fire regimes (exposure). A first feedback subsystem links fire regimes to atmospheric and climate dynamics within the Earth System (sensitivity), while the second feedback subsystem links changes in fire regimes to changes in the provision of ecological services and to their consequences for human systems (adaptability). We then briefly illustrate how the framework can be applied to two regional cases with contrasting ecological and human context: boreal forests of northern America and African savannahs.

Keywords Climate · Earth system feedback · Ecosystem services · Emissions · Fire regime · Global change · Human-environment system · Land use · Vulnerability analysis

1. Introduction

In 2003 large fires in southeastern Australia, western Canada, Mediterranean Europe, and southern California have again drawn considerable public and political attention to fire as a phenomenon through which ecological and human dynamics collide, at times in a critical fashion. This recent episode reinforces concerns that were raised for tropical forest regions after the previous El Niño cycle of 1997/98 (Siegert et al. 2001; Page et al. 2002; Cochrane 2003). Fires are indeed critical elements in the Earth System, linking climate, land use, and vegetation. Fire disturbs a greater area over a wider variety of biomes than any other natural disturbance, and has done so for millennia (Clark et al. 1997; Pyne 2001). Globally 200–500 Mha burn annually (Goldammer and Mutch 2001). Vast areas of savannahs (200–400 Mha), circumboreal forest (5–15 Mha), and many other forest, woodland, and shrubland ecosystems are affected. Fire ignition, propagation, and impacts depend on the interactions among climate, vegetation structure, and land use, on local to regional scales (e.g., Lavorel and Steffen 2004). Therefore fires and their effects on terrestrial ecosystems are potentially highly sensitive to global change. Furthermore, large or intense fires can cause dramatic changes in the structure and functioning of ecosystems (Dale et al. 2001). By contributing significantly to greenhouse gas (releasing 1.7–4.1 Pg of carbon) and aerosol emissions, and modifying surface properties, fires affect not only vegetation but also climate. Fires and the vegetation changes they cause therefore have significant impacts on the atmosphere, biogeochemical cycles, and a variety of ecosystem services such as carbon sequestration, soil fertility, grazing value, biodiversity conservation, and tourist attraction. Fires must therefore be included in global and regional assessments of vulnerability to global change (Houghton 2001).

Vulnerability is the compound outcome of exposure, impacts on ecosystem services (termed 'sensitivity'), and adaptability of natural and human systems (Turner et al. 2003). In the case of fire, and taking an ecologically centred approach to vulnerability, exposure resides in the combined changes in climate, atmospheric composition, land use, and biodiversity (e.g., invasions) that are triggered regionally or locally by global change. Sensitivity is the range of impacts on ecological and human systems that result in changes in the delivery of ecosystem services. Adaptability is the degree to which policies, economics, or other human factors will respond to cope with the impacts of fire on ecosystem services.

Quantifying regional vulnerabilities to fire therefore goes beyond refining the understanding of cause–effects relationships, such as the classically studied effects of climate on fire risks, the impacts of land use on fire frequency or intensity, or the quantification of emissions from burnt areas to the atmosphere (Figure 1, arrows). Instead, assessment of regional vulnerabilities resulting from biophysical and human consequences of changed fire regimes under global change scenarios requires an integrated approach. Previous studies have called for

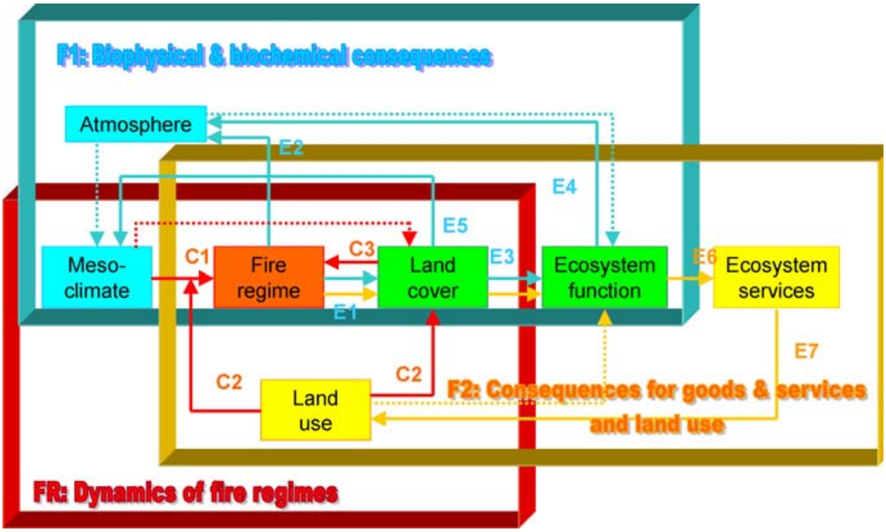

Fig. 1 Integrated fire research framework. The framework presents relationships among different compartments of the human-environment system involved in fire causes and effects. These are organised into one control loop on fire regimes (FR, red box and arrows) and two feedback loops, the first one driving consequences of fire for biophysical and biochemical processes (F1, blue box and arrows), and the second one (F2, yellow box and arrows) driving consequences of fire for ecosystem services and land use. Full arrows indicate topics of direct concern to integrated fire research, while dotted arrows represent other important, often indirect effects. Arrows representing different causes (C) and effects (E) are numbered as referenced in the text

similar integrated approaches for specific regions or biomes (Chapin et al. 2003 for Alaska; Cochrane 2003 for rainforests). Here we present a generic conceptual framework for such integrated, multidisciplinary studies. The framework is structured around three interacting, partially nested subsystems whose dynamics contribute to vulnerability. The first subsystem describes the controls on fire regimes (Figure 1, FR). A first feedback subsystem links fire regimes to atmospheric and climate dynamics within the Earth System (F1), while the second feedback subsystem links changes in fire regimes to changes in the provision of ecological services and to their consequences for human systems (F2). We then briefly illustrate how the framework can be applied to two regional cases with contrasting ecological and human context: boreal forests of North America and African savannahs.

2. Changing exposure: Cascading global change impacts on regional fire regimes

Fires occur because of a combination of predisposing weather, fuel conditions, and ignition agents (Stolle et al. 2003). Ignition may result from human activities or natural events. Fire regimes can hence be defined by frequency, type, and predominant cause of fires in each region. Fire regime maps (Figure 2) show current exposure for each region of the globe. Quantifying fire-related vulnerability of different regions to global change will require maps of future exposure, i.e., of future fire regimes. To achieve this objective, a better understanding of the relative contributions of climate, vegetation, and human activities in driving fires across regions, and of the interactions between these factors, is required (Eva and Lambin 2000).

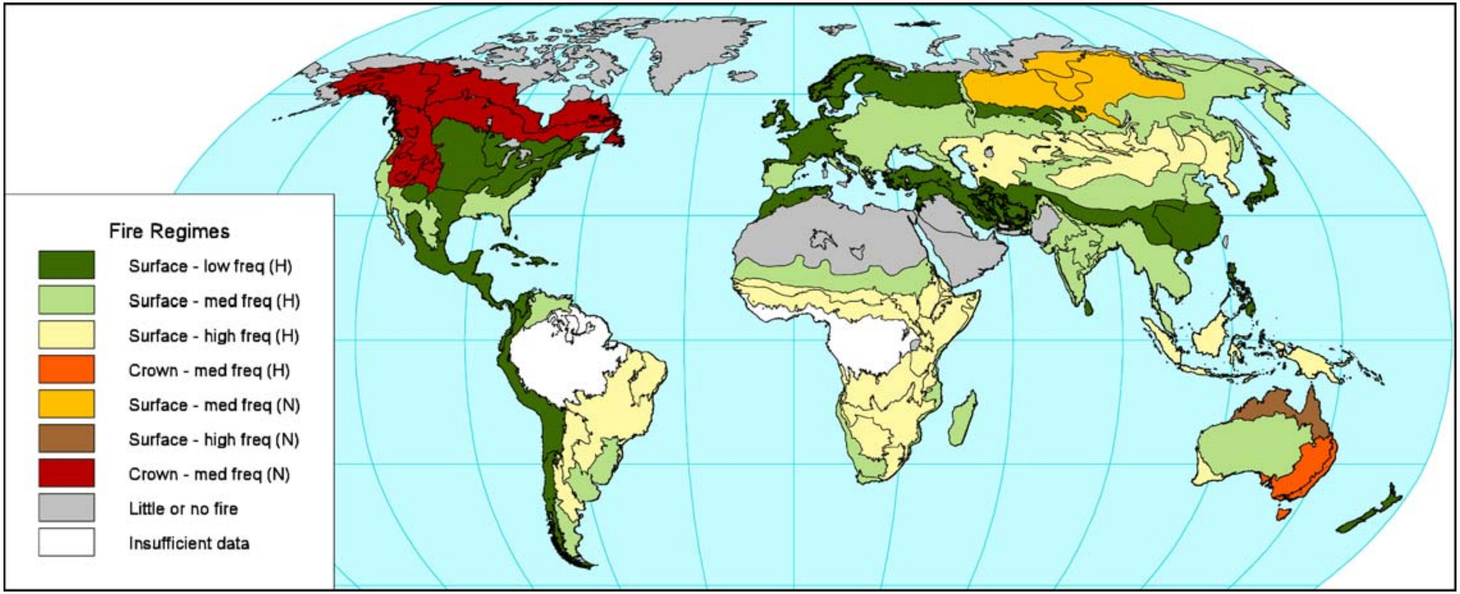

Fig. 2 Global map of estimated fire regimes. This map displays the predominant cause, type, and frequency of fire for slightly modified FAO ecological zones (www.fao.org/forestry/fo/fra/index.jsp). This map is an estimate because fire statistics for some regions are limited (Conrad et al. 2002; Stocks et al. 2002; www2.ruf.uni-freiburg.de/fireglobe/welcome.html#Global Fire Inventories and Models). Fire cause is classified by the predominant source either natural or human (N or H in legend); no attempt was made to distinguish between accidental and intentional human-caused fires. Fire type was either surface or crown. Three levels of fire frequency were used and they correspond to a fire cycle of more than 200 years, between 20 and 200 years, and less than 20 years, respectively, for low, medium, and high frequency. These are arbitrary classes, however; a fire frequency of 20 years roughly separates forests from grasslands and savannahs. Using a combination of ecological zones and political boundaries may refine this map, as fire management policies and cultural practices can vary from country to country. There are additional aspects of fire regime including fire intensity, fire size, fire severity (amount of organic material consumed), and season of fire, which were not incorporated in this map for the sake of simplicity

2.1. Climate and weather (Figure 1, C1)

Climate influences fuel availability and flammability, ignition by lightning, and fire propagation after ignition. Fire is thus strongly linked to the variations of climate and weather through space and time (Swetnam 1993). Climate and short- to medium-term weather influence fuel availability. For instance, El Niño Southern Oscillation events have a significant influence on fire activity in Australia (Williams and Karoly 1999), southeast Asia (de Groot et al. this issue; Murdiyarso and Adiningsih this issue), the southwestern U.S.A., and Argentina by affecting fine fuel production (Kitsberger et al. 2001). Fire danger is also highly sensitive to daily variability in air temperature, relative humidity, wind speed, and precipitation, all of which control fuel moisture, and hence whether a fire will smoulder, burn, or go out after ignition. In circumboreal regions for example, much of the forest area burnt yearly burns within just a few days during favourable synoptic weather patterns (Flannigan and Wotton 2001; Skinner et al. 2001). Knowledge of such preconditions may help in the development of efficient forecasting systems for 'extreme' fire seasons (Beckage and Platt 2003), thereby aiding the development of more effective wildfire fighting strategies (de Groot et al. this issue).

Climatic change will affect fire frequency. Evidence is already accumulating from records of fire regimes that recent changes have coincided with increases in both extent and intensity of fires in several regions (e.g., Swetnam 1993; Flannigan and Harrington 1988; Pausas 2004). Many studies using general circulation models (GCMs) have anticipated significant increases in fire weather and fire danger over large sections of Australia, Europe, North America, and Russia (Stocks et al. 1998). Climate change is also likely to affect ignition by lightning, which is common in sparsely populated regions like circumboreal forests and Australia, and is determined by atmospheric moisture and instability. The GISS 2xCO_2 scenario for the U.S.A. modelled a 44% increase in lightning-caused fires with an associated 78% increase in area burnt (Price and Rind 1994).

2.2. Human activities (Figure 1, C2)

While natural ignition occurs relatively infrequently on a global scale, human ignition associated with land use is widespread (Figure 2). Fire plays multiple roles in land use: it is a tool for hunting, clearing forests, maintaining grasslands, controlling pests, and managing crops (Eva and Lambin 2000). Environmental historian Stephen J. Pyne has narrated the story of how fire and humanity have interacted to shape the Earth in his Cycle of Fire suite of books (e.g., Pyne 1997). Today, in dense humid forests, fires are used for permanent land conversion or as part of slash-and-burn agricultural systems. During dry years, fires that escape during land clearing can destroy unmanaged or protected forests (Cochrane et al. 1999; Eva and Lambin 2000). In dry deciduous forests of the tropics including a large part of mainland Southeast Asia, as well as in savannahs and seminatural grasslands, frequent burning is used to prevent woody encroachment, to selectively enhance grass production, for obtaining a green flush (Mbow et al. 2000), or, in the case of patch burning early in the burning season, to protect the landscape from later destructive fires (Laris 2002). In recently created pastures within forests, burning controls weeds, pests, and woody recolonisation. Prescribed fires are also used in forest management for reduction of wildfires, site preparation for planting, and wildlife habitat management.

Where fires are mostly ignited by human activities, there is an inverted-U-shaped relationship between land use intensity and fire frequency: unoccupied ecosystems do not burn frequently; systems dominated by slash-and-burn agriculture or pastoralism favour fires as a land management tool and modify vegetation accordingly; and systems based on mechanised farming or intensively managed plantations have suppressed fires (Lambin et al., unpublished). Note that cause and effect may be confounded in some cases, as slash-and-burn systems not only modify fire regimes and land cover but are also carried out preferentially in sites where vegetation species are fire adapted. This relationship results from trade-offs between the benefits of fires, described above, and the risks to human life, capital, and production caused by fires. As land use intensifies, fires are substituted by other inputs (labour, machinery, inorganic fertilisers), the density of human infrastructures or productions that could be threatened by fires increases, and available fuel generally decreases. New policies regulating the use of fires may rapidly alter fire regimes. In tropical regions, extreme droughts may increase escapes from slash-and-burn activities and opportunistic use of these high flammability circumstances for land conversion. With agricultural intensification, the role of fire may switch from forest clearing to burning agricultural residues. In the longer term, mainly in developed countries, fire suppression is now believed to lead to fuel accumulation and thus increases the risk of large and severe accidental fires (Agee and Hulff 1987). Evidence for this view has been found mostly in developed countries, as exemplified by the 1988 Yellowstone fire event in western United States. Yet the overall influence of fire suppression on fire regimes is still contentious, e.g., in chaparral and boreal forests (Keeley and Fotheringham 2001), partly because impacts are confounded with other human influences like landscape fragmentation.

2.3. Land cover (Figure 1, C3)

Land cover controls fire propagation, in interaction with weather. Land cover is controlled by both climate and land use. Different land covers have widely differing flammabilities depending on species composition, stand age and density, microclimate, and soil conditions. During extreme drought most fuel becomes flammable (Hély et al. 2001; Román-Cuesta et al. 2003), whereas during lower-risk conditions the nature of land cover (e.g., Vásquez et al. 2002) and the connectivity of flammable vegetation mostly determine surface fire spread (Turner and Romme 1994; Rupp et al. 2000). Small increases in the abundance or spatial continuity of flammable vegetation allow large fires to arise (Turner and Romme 1994). Landscape fragmentation by agriculture or forestry may inhibit the spread of fires, a property long known by rural populations using fire as a management tool (see above). Conversely, when agricultural land is abandoned, or the intensity of pastoral use becomes very low, spatial connectivity of woody vegetation increases again. This was the case in the 1980s–90s in Mediterranean Europe, when the combination of drier-than-average conditions and reforestation of traditional agropastoral landscapes allowed exceptionally large fires to develop (Moreno 1998). In rainforests, however, forest fragmentation caused by selective logging increases rather than decreases fire penetration into the forest (Holdsworth and Uhl 1997; Nepstad et al. 1999), priming a positive feedback where secondary forests foster subsequent fires and degradation (Cochrane et al. 1999). This way, increasing density and connectivity of clearings in rainforests facilitates fire spread and enhances overall fire susceptibility by exposing increasing fractions of the forest to fire-prone edges (Cochrane 2001).

Finally, the direct and indirect effects on vegetation of atmospheric CO_2 concentration and changed water balance may also affect fire regimes. Much uncertainty remains about the nature and magnitude of these effects (Weber and Flannigan 1997), although models for simple systems such as savannahs suggest that CO_2 may be a major control on the balance between land cover (tree vs. grass) and fire regimes (Bond et al. 2003a).

2.4. Future fire regimes

'Exceptional' fire seasons that made the headlines in 1997/98 in the tropics and in 2002/03 in temperate latitudes have highlighted consistent chains of causes in recent large fire events. They reflected the combination of preconditions resulting from regionally strong effects of El Niño (i.e., exceptional droughts) and critical synoptic weather with ongoing or recent land use change (e.g., exotic pine plantations on the edge of suburbs). Such was the case for example in southeastern Australia, where in January 2003 half a million hectares burnt in less than a month and where the capital city, Canberra, incurred significant damage in a single day of extreme conditions (Lavorel and Steffen 2004). Such catastrophic events raise questions that challenge global change science: What conjunction of biophysical and human conditions triggered this disaster? Which thresholds were exceeded? How close is the system to these thresholds under its average conditions? Will such catastrophic events become more frequent as global change continues and possibly accelerates?

Globally, maps of future fire regimes can be produced with models of vegetation-fire dynamics driven by scenarios of climate and land use change. These can be based on relatively simple mechanistic models that estimate frequency and extent of fires at the regional scale from climate and human density (e.g., Venevsky et al. 2002), or on statistical models relating observed fire regimes to climate and land use variables (e.g., Cardoso et al. 2003). To further document, understand, and predict exposure to fire, the spatiotemporal patterns depicted in global maps of active fires, burnt areas, and fire regimes (Figure 2) need to be related statistically within each region to data on ecosystem structure, land use, and socio-economic factors including the historical dimension of interactions between society and fire regimes. Complementary local surveys are required to document motives for fire ignition as part of today's land use systems. More sophisticated models linking land cover to fire regimes should also incorporate transient vegetation dynamics (Bachelet et al. 2000; Thonicke et al. 2001), plant species migration (Neilson et al. 2005), and effects of landscape heterogeneity owing to physiography, land use, and past fires (Foster et al. 2003). Lastly, indirect effects caused by other disturbances dependent on weather (insect outbreaks, windthrow, grazing) can modify flammability and may cause surprises in future fire regimes (Weber and Flannigan 1997).

3. Earth system sensitivity to changed fire regimes: Global fire – atmosphere – climate feedbacks (Figure 1, F1)

Quantifying biophysical consequences of changed fire regimes on Earth System dynamics requires consideration of the full feedback loop linking effects on land cover, emissions to the atmosphere, and impact of these on climate.

3.1. Fire – land cover link (Figure 1, E1)

Disturbances like fire are a key determinant of land cover. Ecosystem resilience to fires differs widely across regions depending on their evolutionary histories and whether fires ultimately reduce or increase flammability. Most dense humid forests regenerate slowly and are destabilised after fire because, under characteristic low fire return intervals, floras contain few fire-adapted species (e.g. Goldammer this issue). Increased fire frequency converts land cover to grassland or woodland dominated by species that tolerate fire and possibly require it for their regeneration, inducing a positive feedback through increased flammability (C3).

In contrast, boreal or eucalypt forests, Mediterranean shrublands, seasonal tropical forests, savannahs, and prairies that have been influenced by fire for millennia are highly resilient as long as fire frequency, severity, and timing with respect to the growing season remain within historical bounds (Goldammer 1993, this issue; Howe 1993; Naveh 1994). The stability of these ecosystems stems from species biology (e.g., Lavorel 1999; Pausas et al. 2004) and the transient reduction of flammability by fire. Recurrent fires that gradually lower nutrients stocks (Crutzen and Andreae 1990; Wan et al. 2001) may however induce land cover changes over the long term, even in more resilient ecosystems. Hence fire effects on land cover operate at several time scales, and the adjustment between vegetation and changed fire regimes involves time lags (Weber and Flannigan 1997). Lastly, during periods of rapid climate change such as the one we are currently experiencing, fire may act as an accelerating factor for community reassembly and vegetation (Brubaker 1986). Fire effects on vegetation may therefore be much faster than direct effects of climate change on vegetation (Rupp et al. 2000).

3.2. Fire/ecosystem function – atmosphere links (Figure 1, E2–4)

Currently, biomass burning contributes significantly to greenhouse gases emissions and is an important source of pollution. The global annual carbon flux to the atmosphere from global savannah and forest fires is estimated at 1.7–4.1 Pg (Dixon et al. 1994). Emissions of other gases are estimated at 39 Tg of CH_4, 20.7 Tg of NO_x, and 3.5 Tg of SO_2 annually (Andreae and Merlet 2001). This results in estimated contributions from biomass burning to global annual emissions of 40% for CO_2, 32% for CO, 10% for methane, 38% for tropospheric ozone, and over 86% of black soot (Crutzen and Andreae 1990). Globally, black carbon formation amounts to about 0.5% of carbon lost as CO_2 (Kuhlbusch and Crutzen 1995).

The magnitude of the carbon flux from fires can make a region a carbon sink or source. The current sink calculated for the U.S.A. (Schimel et al. 2001) may result in part from fire suppression over several decades (Tilman et al. 2000). In contrast, the net carbon balance of Canadian forests has changed from a strong sink (1900–1980) to a weak source (1980–90s) as a consequence of notably increased fire activity (Kurz and Apps 1999). In addition to current fire activity, postfire regrowth accounts for a substantial part of the temporal variability in carbon fluxes. Studies in the boreal forest suggest that after fire these areas are a carbon source for a few years and may take 20 to 30 years before the carbon sink returns to the prefire state (Amiro et al. 2002). Estimations of emissions from the 1997 fires in Indonesia indicated that 0.81–2.57 Gt of carbon were released to the atmosphere from peat and other vegetation, representing 13%–40% of the mean annual global carbon emissions from fossil fuels (Page et al. 2002). For the same period, CO_2, CO, CH_4 and NO_x emissions reached daily rates of 1.28 Mt, 0.219 Mt, 0.0123 Mt, 0.0393 Mt, and 0.108 Mt, respectively, significantly exceeding the emissions from the Kuwait oil fires of 1991 (Levine 1999).

Understanding the relationship between biological, chemical, and physical factors that influence biogenic emissions and the effects of fires on trace gas production is required to project biogeochemical and atmospheric impacts of fire under changed climate and land use. The contribution of biomass burning to long-range transport of chemical pollutants (e.g., in the northern hemisphere, Wotawa and Trainer 2000) and how climate variability affects this transport also need to be considered.

3.3. Land cover/atmosphere – climate links (E5)

Over the longer term, fire can alter regional climate when it induces switches in vegetation type (e.g., from coniferous to deciduous forest or from forest to grassland) and thereby fosters fundamental changes in ecosystem surface properties such as albedo, temperature, and hydrology (Amiro et al. 1999; Pielke 2001). Emissions from biomass burning affect the chemistry of the atmosphere (Andreae and Merlet 2001). Notably they contribute to increasing the radiative forcing by greenhouse gases, and thereby to global warming, which in turn leads to more fires (Kurz et al. 1995). Positive forcing by black carbon may almost balance the net cooling effect of other aerosols (Jacobson 2001). In addition, smoke aerosols impact regional and probably global radiation budgets. In the short term, smoke can have a positive feedback on weather and fire activity by promoting lightning ignitions (Lyons et al. 1998) and reducing local precipitation (Rosenfeld 1999). Ultimately, by altering regional climate, emissions from fire are likely to feed back to climatic preconditions for fire, with great uncertainty regarding the degree of amplification or buffering.

4. Human sensitivity and adaptability to changed fire regimes: Fire – ecosystem services – human systems feedbacks (Figure 1, F2)

Understanding feedbacks from fire to ecosystem services and to human systems is critical to the assessment of the sensitivity and adaptability of human-environment systems to changing fire regimes. Here we start sketching some of the elements of these feedbacks taking a land surface perspective. Full consideration of the complexities of the dynamics of the human system (see, e.g., Chokkalingam et al. this issue) would require the inclusion of a whole additional set of components and interactions to the framework to address, for instance, institutions, policies, technological innovations and choices, perception of risk, and human well-being.

4.1. Land cover–ecosystem function link (Figure 1, E3)

Fires affect biomass production, soil carbon, and nutrient dynamics. Fires can produce a short-term increase (Knapp and Seastedt 1986; Hughes et al. 2000) or decrease (Amiro et al. 2000; Hicke et al. 2003) in aboveground primary production, the magnitude and duration of which depend on vegetation type, climate, soils (DeBano 1998), initial stand age (Wang et al. 2001), and landscape pattern (Turner et al. 2001). Modelled fire frequencies of 50, 200, and 500 years in the northern hemisphere reduced soil nitrogen stocks by 50%, 30%, and 5%, respectively. Subsequently productivity was limited by nitrogen, unless nitrogen fixation was present, and phosphorus became limiting (Vitousek unpublished). Whether soil nutrients increase or decrease under contrasting fire frequencies depends on fuel and vegetation types, fire intensity and severity, soil type, and changes in primary production (Wan et al. 2001). Lastly, regular burning reduces the litter layer, so that water availability for plants decreases, not only by reducing mulching by vegetation and litter, but also by intensifying runoff. Fire effects on ecosystem function therefore operate over multiple time scales. Short-term responses of biogeochemical cycles to fire are likely to influence the structure and function of ecosystems in the long term (Amiro et al. 2000; Wan et al. 2001; Hicke et al. 2003). Finally, although several large controlled experiments (Lindesay 1996; Cofer et al. 1998) have provided detailed data on the biophysical impacts of fires, better understanding of processes is critical to the ability to extrapolate from a few intensive study sites to entire regions.

4.2. Ecosystem function–services link (Figure 1, E6)

By modifying land cover and ecosystem functioning, changed fire regimes can strongly impact the delivery of services. The effects on ecosystem functioning described above impact essential services such as carbon sequestration, maintenance of soil fertility, atmospheric quality, and climate regulation. A range of other services are affected by changed fire regimes or catastrophic fires. These start with the direct products people can obtain from harvesting. For instance, in the wetlands of southern Sumatra repeated fires transform diverse swamp forests, from which a diversity of products are obtained, into gradually more degraded stands of fire-adapted *Melaleuca cajuputhi* and grasses, with continually decreasing quality of harvestable wood (Chokkalingam et al. this issue). As another example, the quantity and quality of water available from catchments depends on the vegetation cover. In the short term, floods may follow large fires because of increased runoff and reduced evapotranspiration. In the longer term, adjustment between landscape vegetation and fire regimes modifies water resources.

Changes in fire regimes can also have considerable impacts on biodiversity and the services it provides to humans. In regions where fires have been infrequent, shorter return intervals decrease biodiversity (Russell et al. 2002; Johnson and Cochrane 2003; Goldammer this issue). Negative effects of changes in fire regimes on biodiversity can also be indirect. For example, exotics with a high fuel load increase fire frequency, gradually replace less flammable and fire-intolerant native species, and can thereby foster more invasions (D'Antonio et al. 1999). In contrast, in ecosystems where fires have been a major evolutionary constraint, fire suppression reduces plant and animal diversity because it eliminates fire-adapted species and reduces landscape heterogeneity (Baker 1992; Glenn et al. 1992; Howe 1993; Bowman 2000). Fire suppression can offset the complex balance among vegetation, herbivores, and fire regimes, as has been the case in the Intermountain West region of North America (Hessl 2002). Overall however, consequences of fire regimes for biodiversity, human health, landscape aesthetic, or recreational values and their trade-offs with other services such as carbon sequestration are scarcely documented (but see Murdiyarso et al. 2002).

4.3. Ecosystem services – land use link (Figure 1, E7)

Changes in vegetation cover induced by fires may have an impact on land use, in particular when the initial fires were not accidental. In some tropical countries, national land allocation policies are the main driver for forest conversion by fire (Stolle et al. 2003). In Indonesia, both small farm and large plantation holders use fire to clear land, and fires are sometimes used in land conflicts between them (Murdiyarso and Adiningsih this issue). In dry years such as during El Niño events, however, fires affect a much larger area than initially intended, thus opening new land for development and forcing a revision of land allocation plans (Tacconi et al. this issue). Because the time scale of the institutional response to a severe fire event is often longer than the time scale of the opportunistic land occupation by local stakeholders after a fire, potential for land-use conflicts is high. Salvage harvesting of timber after an accidental fire is another example of land use induced by fires. This practice creates negative feedback as salvage harvesting decreases the regenerative potential of stands, in addition to having other negative impacts on ecosystem services (Van Nieuwstadt et al. 2001; Lindenmayer et al. 2004). Fire events can also stir modifications in land management practices in addition to land conversion, for example, adoption of alternative logging methods, tree lopping, drainage of peatlands, and irrigation (see, e.g., Chokkalingam et al. this issue).

The feedback loop linking fires, ecosystem services, and land use may have important economic implications even in developed countries. Future changes in fire regimes are of great concern to the forest industry as decreases in production and increases in the cost of forest protection from fire may threaten commercial viability (Weber and Flannigan 1997; Irland et al. 2001). In Spain, entire plantations were lost in the 1980s and '90s to large and intense fires, after which replanting was no longer economically viable. In the design of reforestation and afforestation plans for carbon sequestration, costs of fire protection may be important elements as fires are likely to turn forests into sources of carbon to the atmosphere (Noble and Scholes 2001). If ecosystem services threatened by fires have a high market value, this feedback will be negative as fire protection costs will be recovered. But if these services have a low market value, there is the risk of positive feedback through land use abandonment in fire-prone areas, leading to more natural and accidental fires. Policies have thus a major role to play in the reduction of vulnerability of local and regional systems to fire.

To assess the adaptability of human-environment systems to fire more systematically, models incorporating the interaction between fire-vegetation-climate dynamics and land use change processes are needed (Chapin et al. 2003). Yet knowledge of feedbacks to land use decisions from fire-induced changes in ecosystem services is limited so far to anecdotal evidence and speculation that large enough fires can trigger land use conversion. Typical pathways through which accidental and intentional fires trigger land use changes include policy and economic responses to fire threats to ecosystems and populations. In Southeast Asia for instance, following the 1997–98 fires the Regional Haze Action Plan and corresponding national plans for monitoring, prevention, and mitigation of forest fires were aimed at modifying land use and fire (Qadri 2001). Such feedbacks from fire-induced changes in ecosystem services to the driving forces of land use change (e.g., land use policies and economic factors that determine land use decisions) have received scant attention so far and it is a new area of research. The effectiveness of such plans also needs to be assessed, in particular to evaluate their relative weight in modifying fire risk compared with other driving forces of land use change such as, in Indonesia, macroeconomic policies, changes in the price of palm oil, and administrative decentralization.

5. Regional fire – related vulnerability: Some examples

5.1. Boreal forests of North America

5.1.1. Changing Exposure (Figure 1, C1–C3)

The boreal forest in North America extends from Atlantic Canada in a broad swath to Alaska. Fire is the major stand-renewing agent for much of the boreal forests of North America, greatly influencing the structure and function of the forest. Wildfire, typically crown fire, is a regular feature of much of the North American boreal forest (Figure 2; Stocks et al. 2002). Current estimates are that an average of 3 Mha burn annually in the boreal forests of Canada and Alaska, and there is a growing global awareness of the importance, and vulnerability, of this region with respect to projected future climate change (Flannigan et al. 2001). Area burnt increases of 50%–100% are possible in Canada this century because of more conducive fire weather as modelled by GCMs (Flannigan and Van Wagner 1991; Flannigan et al. 1998).

Additionally, recent work suggests a 25%–50% increase in human-caused fire ignitions in some boreal forests of Canada because of climate change (Wotton et al. 2003).

Interactions between climate and land-cover changes may lead to rapid modifications in fire regimes. In southwest Alaska, a simulated temperature increase of 1 °C per century increased total area burnt per decade by over 200% by influencing, at different time scales, water balance (fast) and vegetation cover (slow) (Rupp et al. 2000). In addition, particular weather sequences were likely to cause local switches to fire-maintained grassland. Another example of a nonlinear interaction comes from the Alaskan interior, where simulations suggest that fire suppression will lead to reductions in area burnt in the short term, while over the long term successful fire suppression will lead to a higher proportion of flammable vegetation and a likely increase in fire occurrence, especially near communities (Chapin et al. 2003).

5.1.2. Fire – atmosphere – climate feedbacks (Figure 1, F1)

One feedback of fire is on the carbon dynamics of the boreal forest (Figure 1, E2–4). The net carbon balance of Canadian forests has changed from a strong sink (1900–80) to a weak source (1980–90s) because of notably increased fire activity (Kurz and Apps 1999). These boreal forest fires release carbon through direct combustion emissions that can be estimated given the size of the fire and the weather conditions under which it burnt. For all Canada, the direct combustion emissions are at an average rate of 1.3 kg carbon m^{-2} of burnt area. Over the last 40 years, these direct combustion emissions amount to almost 20% of the amount of carbon released through fossil fuel emissions in Canada and during active years is comparable to fossil fuel emissions (Figure 3; Amiro et al. 2002). In addition to direct combustion losses of carbon, fire also influences carbon flux by changing photosynthesis and respiration rates in regenerating vegetation. The postfire carbon dynamics are less well known than the combustion losses, but are likely of at least the same magnitude. In the Canadian boreal forest, initial daytime carbon flux may only be recovered after 30 years (Amiro et al. 1999).

Weather and climate are key factors for fire activity, but fire may influence the climate (Figure 1, E5). There is the possibility for positive feedback, whereby climate change causes more fires, which then release more carbon from the forest, increasing atmospheric greenhouse gas concentrations. Although this phenomenon could be global, we expect some self-limiting factors to stop a run-away scenario. For example, in boreal western North America, a warming-induced increase in fire frequency, increasing the extent of deciduous forests, could act as negative feedback to regional warming because of their higher albedo and evapotranspiration, and therefore decreased sensible heat flux as compared with presently prevalent conifers (Chapin et al. 2000).

5.1.3. Fire – ecosystem services – human systems feedbacks (Figure 1, F2)

Interactions between climate change and fire could have socioeconomic implications in terms of adaptive fire management strategies, age class distribution, and other issues such as biodiversity. For example, future changes in fire regimes are of great concern to the forest industry as decreases in production and increases in the cost of forest protection from fire may threaten commercial viability in the boreal forest (Weber and Flannigan 1997; Irland et al. 2001).

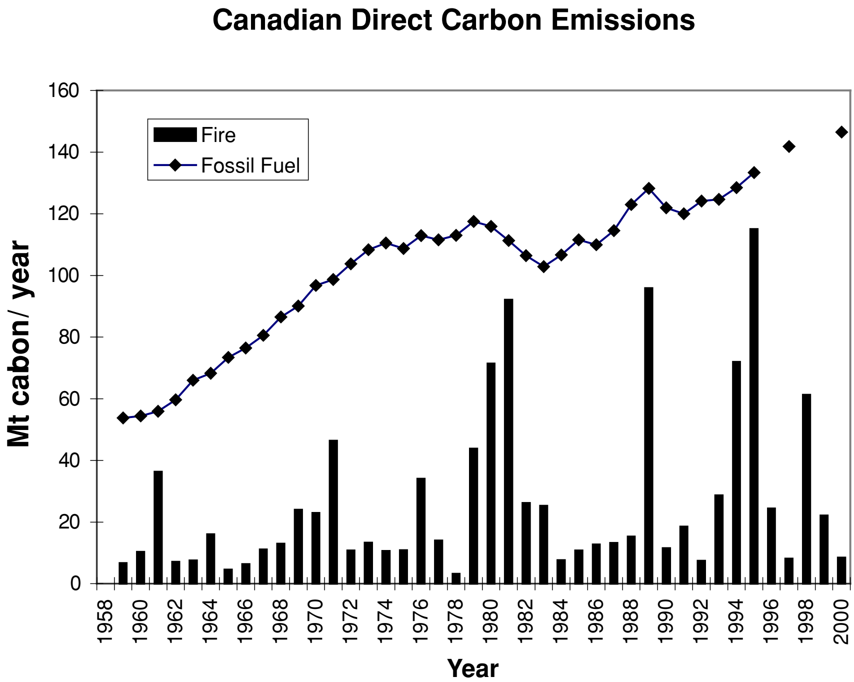

Fig. 3 Direct carbon emissions from large fires (>200 ha) for Canada, 1959 to 1999. Carbon released was determined from the fuel consumption as calculated by using the Canadian Fire Behaviour Prediction System. On average about 27 Tg of carbon is released directly from flaming and smouldering combustion in the boreal forests of Canada, to which are added amounts of a similar magnitude resulting from decomposition of the dead organic material. During extreme fire seasons like 1995 (direct emissions from fire exceeded 115 Tg C per year) the carbon released approaches the carbon emissions from fossil fuels for Canada (150 Tg C per year). Error bars are estimated bounds of uncertainty (adapted from Amiro et al. 2002)

5.2. African savannahs

5.2.1. Changing exposure (Figure 1, C1–C3)

Fire in Africa occurs mainly in savannahs (Figure 2). Fire has long been recognized as an essential determinant of the structure and function of African savannahs (Trollope 1982; Scholes and Walker 1993). The fraction of the African savannahs area that burns annually is quite similar to the fraction in savannahs on other continents, but Africa has half of the global extent of this fire-prone ecosystem.

Ecosystem evolution in Africa has been influenced by a complex set of interactions between herbivores, fire, humans, climate, and soils. There is emerging evidence that general control over the fraction of landscape burnt is by climate (Figure 1, C1): smaller fractions in dry areas, higher ones in mesic areas on infertile soils, up to the rainforest limit, where burnt area drops dramatically. Climate and short- to medium-term weather also influence annual fire extent through their effects on fuel availability. In southern Africa, drought reduces fuel and hence burning activity (Barbosa et al. 1999). The quantity of fuel available, however, is also highly conditioned by tree cover and herbivory (Figure 1, C3). Recent simulations using a dynamic global vegetation model suggested that most of the eastern half of southern

Africa could support much higher stem biomass without fire, and that vegetation would be dominated by trees instead of grasses. Areas receiving less than 650 mm of rain showed changes in tree density and size but no trend of changing composition to forest (Bond et al. 2003b).

Humans and their ancestors have set fires in Africa for over a million years to create a suitable environment for grazing and browsing by wild and domestic herbivores (Figure 1, C2). For many farmers, fire is an essential tool used deliberately for hunting, clearing land, maintaining grasslands, controlling pests, and removing dry vegetation and crop residues. In savannahs, the main purpose of burning is to prevent the replacement of the herbaceous strata by woody biomass and to enhance, in the short-term, the production of some grasses. While weather and rates of vegetation senescence define the predisposing conditions for fires (the fire season), land use influences the exact timing of burning within this window of opportunity. Two recent studies suggest that farmers and pastoralists seek to burn most grasses early in the season, as it is the safest and most beneficial way to burn. In Senegal the main reason for early season burning is to stimulate a 'green flush' from perennial grasses and to protect landscapes against later and more destructive fires (Mbow et al. 2000). In Mali, although the green flush is clearly a motivation for burning, herders and hunters use early burning to gain control over later fires by fragmenting the landscape (Laris 2001).

5.2.2. Fire – Atmosphere – climate feedbacks (Figure 1, F1)

Fire and the continental carbon and nutrient balance (Figure 1, E2–4): Fire can be seen as one of the largest anthropogenic influences on terrestrial ecosystems after urban and agricultural activities (Bond and Van Wilgen 1996). Fire alters the pathway of carbon cycling, reducing the flow of litter to the soil (directly and indirectly, via herbivores) and changing the forms in which it enters the soil (increasing the quantity of highly resistant forms, such as charcoal and black carbon) and the atmosphere (favouring carbon monoxide, methane, and non-methane hydrocarbons). Results from long-term fire trials conducted in Kruger National Park suggest that organic carbon in the topsoil increases in areas from which fire has been excluded, from $1.9 \pm 0.15\%$ to $2.2 \pm 0.14\%$. Annual burning significantly decreased the light fraction carbon from 9.8% to 7.3% of the total carbon (Jones et al. 1990). About two thirds of the nitrogen in savannah fuels is converted to various nitrogenous gases during a fire. A large part of this emitted nitrogen falls back on terrestrial ecosystems in the subcontinent as dry or wet deposition, but about one third is exported over the oceans, where it is probably a significant driver of phytoplankton net primary production in the southern Atlantic and Indian oceans. Thus the ongoing nutrient depletion of the land mass – which may be why African savannahs are so nutrient poor in the first place, which is the main reason they burn so extensively – is nutrient gain for the oceans, where it primes the biological pump that underlies the oceanic carbon sink. Data from long-term fire trials show that soil nitrogen changes are more variable than carbon changes, with some studies reporting no differences and others showing decreases in nitrogen with increased fire frequency. Fire has been shown to increase the rate of biogenic emissions, but that effect is short-lived (Otter et al. 2001; Scholes et al. 2003).

Fire and radiant forcing (Figure 1, E5): The effects of savannah burning on net radiant forcing are extraordinarily complex. The carbon dioxide given off during combustion is assumed to be effectively 'forcing neutral', since it is taken up again in regrowing vegetation. But in the longer term, increases in fire frequency lead to lower tree cover, reducing the amount of carbon stored on the land (Trapnell 1959). The next largest carbon emission is as carbon monoxide, itself not a greenhouse gas, but a tropospheric ozone precursor. An ozone cloud characterizes Southern Africa during the fire season. Other observations and some models, however, point to larger-scale dynamics and lightning as prominent factors in tropical tropospheric ozone distribution (Crutzen and Andreae 1990). The next biggest carbon emission is methane, a greenhouse gas; but if not burnt, the grass would be grazed and end up giving off even more methane. Similarly, non-methane hydrocarbons in the smoke are ozone precursors, but if fire is excluded, the increased tree cover is itself an abundant NMHC source. Fires emit NO_x and N_2O, but less than the soil if allowed to accumulate nitrogen. SAFARI 2000 results show that the particles in the smoke have a net warming effect, but the equivalent net cooling resulting from stimulus of the ocean carbon sink has not been calculated. Overall, if southern Africa became drier on the west side and wetter on the east side, as suggested by climate scenarios, the net impact on fire emissions is unknown. The onset of the summer rains and the pulsing nature of the rainfall are key factors that allow us to understand the interactions between soils, net primary productivity, and atmospheric composition. Climate change predictions indicate a longer dry period with a later starting date for rains. The implications of this scenario are unknown.

Fire emissions and climate (Figure 1, E5): If the net effect of climate change in southern Africa were more fire, and the net effect of more fires were greater climate change, then a positive feedback loop would be set up that will tend to make climate change control more difficult. Conversely, if change led to less fire, or the net effect were less radiant forcing, stabilization would be slightly easier. At present neither sign nor magnitude of this feedback is known.

5.2.3. Fire – ecosystem services – human systems feedback (Figure 1, F2)

Fire, biodiversity, and ecosystem services (Figure 1, E6): Fire has long been used in savannahs and grasslands to create a suitable environment for grazing and browsing by domestic and wild animals by enhancing forage quality and sometimes quantity. Generally fire enhances the quality of forage for a few months, with higher concentrations of mineral nutrients, higher digestibility, and improved structural vegetation characteristics. Fire also has a negative effect on forage availability. As increasing human activity in the savannah biome causes a decline in pastoral area and an increase in grazing intensity, some results suggest that the practice of burning should be reduced rather than advocated, especially because grazing itself may improve forage quality (Schule 1990). In addition, fire-related changes in land cover and forage quantity and quality have large impacts on the economic resources, social benefits, and conservation opportunities that can be gained from managing hunting and wildlife-based tourism.

These two case studies can only incompletely document for each region the elements of the framework for integrated vulnerability analysis, which is a reflection of gaps in our collective knowledge and understanding of the interactions and feedbacks in the framework. The examples do demonstrate, however, that the framework is valid and appropriate for diverse biomes such as boreal forests and savannahs. In addition, the framework may be used as a tool for developing scientific strategy and policy in order to diagnose major gaps in knowledge or transfer of knowledge.

6. Towards integrated assessments of fire-related vulnerability

Assessments of vulnerability of land systems to fire demand regional studies that use a systemic approach that focuses on the two feedback loops described here (Hessl 2002; Chapin et al. 2003; Cochrane 2003). Identifying vulnerable and robust regions with respect to changes in fire regimes resulting from environmental change will require engaging a collection of multiscale and interdisciplinary regional studies. Comprehensive analyses of causes and effects of specific fire events will need to monitor vegetation and biodiversity, soils, atmospheric emissions, and land use at fine scales before, during, and after the fire. Adaptive capacity of human systems to changed fire regimes, in a context of changing socio-economic and climatic conditions, will also have to be assessed. The key issue is to understand how people and societies modify their political, economic, and environmental institutions to prevent a misfit between these institutions and ecosystems under altered fire regimes (Young 2002). Rules governing fire use in an ecosystem characterized by certain predisposing weather, fuel conditions, and ignition agents would be unlikely to remain appropriate if any of these attributes – climate, weather, land cover, and human activities – changed significantly. Some of the recent catastrophic fire events in Indonesia and Australia could be interpreted as a temporary misfit between institutions regulating fire use and management and ecosystem conditions under the climate anomalies associated with El Niño (Tacconi et al. this issue). More profound and longer-term land use changes associated with economic globalization are also a source of misfit between traditional fire-related institutions and ecosystems. These analyses should then help researchers to progressively refine integrated models of fire–ecosystem–human system interactions (Chapin et al. 2003).

Southeast Asia constitutes one of the key regions to which the framework could usefully be applied in order to link history, causes, and impacts of forest fires and to inform on opportunities for policy adjustments. Several authors in this Special Issue have highlighted the wealth of information that has been collected on the impetus of policy needs after the 1982–83 and 1997–98 episodes (see Goldammer this issue; Tacconi et al. this issue). Goldammer (this issue) highlighted the need for interdisciplinary integration of existing approaches and results, which so far has not managed to move from initiatives to implementation. Studies published or reviewed herein (see, e.g., Murdiyarso and Adiningsih this issue; Page et al. 2002) have started to accumulate data on fire–atmosphere–climate feedbacks. These efforts will need to continue, and include consideration of regional teleconnections through transboundary transport of atmospheric pollutants. Individual studies, such as the one reported by Chokkalingam et al. (this issue) of the case of wetlands of southern Sumatra, are making significant progress in documenting the fire–ecosystem services–human systems feedback. Recent progress has specifically been concerned with addressing the complexities of land use dynamics and their relationship to policy. Indeed, moving away from simplifications and considering multiple scales in space and time (Tacconi et al. this issue) has been highlighted as one of the most critical elements to improved understanding to support adaptation and mitigation policy. Finally, case studies and their synthesis point to the diversity of situations across Indonesia in particular and Southeast Asia in general (de Groot et al. this issue; Goldammer this issue). This implies that vulnerability assessments as proposed in this paper would need to be conducted not only over the entire region, but also locally to consider specificities of local human-ecological systems beyond general patterns. Such efforts will be required in order tailor policy that is both relevant and applicable to local resources and conditions.

Collections of regional case studies should ultimately feed into a global synthesis of the vulnerability of human-environment systems to fire under present and future conditions. This exercise of aggregation of regional analyses to a global picture could complement top-down approaches using global vegetation models (Lenihan et al. 1998; Thonicke et al. 2001). Such a synthesis would aim to provide an understanding of the underlying causes for interregional differences that can help shape policy aimed at reducing vulnerability. Fire policy at all scales – from individual land parcel to international region – is influenced by many factors. Climate change mitigation is increasingly one of them, on the scientifically unfounded assumptions that less fire equals less emission equals less climate change. Much research is needed to give governments guidance on this issue and help them move towards fire-related policies and initiatives that consider fire and its complexities as part of the human-environment system (Tacconi et al. this issue).

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