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Linking humans and fire: a proposal for a transdisciplinary fire ecology

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Abstract. Human activity currently plays a significant role in determining the frequency, extent and intensity of landscape fires worldwide. Yet the historical and ecological relationships between humans, fire and the environment remain ill-defined if not poorly understood and an integrative approach linking the social and physical aspects of fire remains largely unexplored. We propose that human fire use is ubiquitous and evidence that historical fire patterns do not differ from non-anthropogenic fire regimes is not evidence that humans did not practice fire management. Through literature review and the presentation of two case studies from the south-eastern USA and tropical Australia, we discuss how the study of fire ecology can benefit from paying attention to the role of humans in three thematic areas: (1) human agency and decision processes; (2) knowledge and practice of landscape fire and (3) socioecological dynamics inherent in the history of social systems of production and distribution. Agency, knowledge of fire ecology and social systems of production and distribution provide analytical links between human populations and the ecological landscape. Consequently, ignitions ultimately result from human behaviours, and where fire use is practised, ignitions result from decision process concerning a combination of ecological knowledge and belief and the rationale of livelihood strategies as constrained by social and ecological parameters. The legacy of human land use further influences fuel continuity and hence fire spread.

Additional keywords: anthropogenic fire, fire-use practices, historical ecology, human agency, landscape fire, socio-ecological systems.

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Introduction

Human activity currently plays a significant role in determining the frequency, extent and intensity of landscape fires worldwide, both as an ignition source (Bond and Keeley 2005) and as a determinant of spread through our ubiquitous influences on earth systems (Vitousek *et al.* 1997). The 'capture' of fire by *Homo erectus* between 0.4 and 1.7 million years before present (BP) (Brain and Sillent 1988; James *et al.* 1989; Rolland 2004) represents a significant factor in human evolution, enabling occupation of harsh climates, cooking and processing of foods, processing of tool materials and manipulation of habitat. Because fire constitutes a significant ecological and evolutionary process in nearly every terrestrial biome on Earth (Bond and Keeley 2005), the use of fire itself dramatically increased the potential for humans to transform landscapes. The deep historical roots of human–fire–landscape interactions have engendered fire-use practices and legacies on every inhabited continent. After thousands of years of fire use, our control of fire remains imperfect (Bowman *et al.* 2009), yet our continued use of fire implies that from a decision-making perspective, the perceived benefits of using fire outweigh the risks.

As a result of the ubiquitous ties between humans and fire, fire ecology has often leant itself to the study of the relationship between human and natural systems (Lewis and Ferguson 1988; Stott 1990; Bowman 1998; Kepe and Scoones 1999; Mistry *et al.* 2005; Marlon *et al.* 2008). However, only in rare instances is adequate consideration given to the social systems that give rise to documented fire practices. The historical and ecological relationships between humans, fire and the environment remain ill-defined if not poorly understood and an integrative approach linking the social and physical aspects of fire remains largely unexplored.

Recent reviews of fire ecology have called for improved understandings of human–fire relationships (Conedera *et al.* 2009; Bowman *et al.* 2011). Bowman *et al.* (2011) made a significant contribution towards this goal by cataloguing the variety of effects humans have on fire regimes and by contextualising and synthesising the pattern of human fire regimes across Earth. These authors call for a multidisciplinary, historical approach that retains its ecological focus.

A limitation of multidisciplinary efforts, however, is that they maintain disciplinary borders throughout the research

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process (CFIR 2004; Porter *et al.* 2006). Maintaining disciplinary isolation potentially results in redundancies and efforts that 'reinvent the wheel'. For example, human ecology has already developed many of the theoretical and methodological tools needed for investigating human–fire relations. Although we agree that a historical and ecological approach is necessary for understanding human fire ecology, it should be informed by social theory. Therefore, research efforts must be truly interdisciplinary, not simply multidisciplinary, and should strive towards formulating transdisciplinary theory. This paper responds to this need by presenting a theoretical orientation for integrating social and natural science in a transdisciplinary fire ecology.

We suggest that developing a transdisciplinary fire ecology requires attention to three conceptual domains commonly employed in the study of human–environment relations:

(1) Human agency and decision-making: humans are sentient actors on the landscape; human agency is neither equivalent to that of other organisms nor is it an exogenous force (Gragson 2005). Recognising human agency compels us to address the question of human cognition and decision-making in the acts of setting, pre-empting and suppressing fire.
(2) Knowledge and practice: human actions both affect and are affected by the natural environment; therefore human decision-making and behaviour with regards to fire use and management constitute adaptive processes that continually refine our imperfect knowledge and practice of fire in order to achieve desired outcomes in the face of changing social and ecological circumstances.
(3) History of social and ecological dynamics: because fire is probably the earliest and most widespread tool used by humans to modify their environment, and humans inhabit every region where fire plays an important ecological role, fire is not merely a biophysical process, but a social process as well. Consequently, the history of fire must be considered within the context of the history of social systems concerned with the production and distribution of material goods. In our view, the history of these social systems cannot be understood outside its ecological context. This component is therefore more accurately termed the history of socio-ecological dynamics and draws on literature from historical ecology (Crumley 1994), socioecological systems (Redman 1999) and land-use, land-cover change studies (Lambin *et al.* 2000).

These conceptual domains provide theoretical context for understanding the relationship between hierarchically nested units of analysis in social and ecological sciences (Allen and Starr 1982; Delcourt and Delcourt 1988; Cash *et al.* 2006; Fig. 1). Human agency provides context for understanding the interaction of individuals with patch- and landscape-level ecology at relatively short intervals of time. Knowledge and practice characterise the interaction of networks of individuals with landscape- and regional-level ecology at moderate time scales. Finally, socioecological dynamics explores the development of social and ecological systems over time and at large spatial scales.

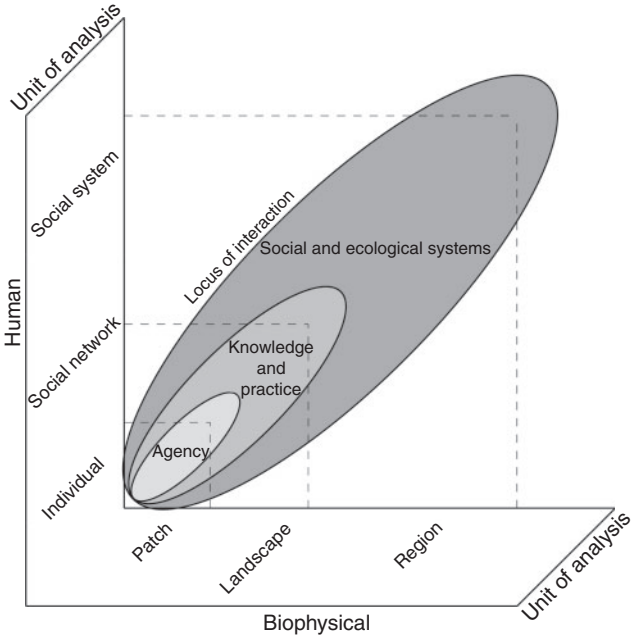

Fig. 1. Featured conceptual domains and corresponding levels of interaction between human and biophysical units of analysis.

In this paper, we discuss the implications of this theoretical orientation for understanding the relationships between human behaviour and fire ecology in general and more specifically the relationships between human fire practices and emergent fire regimes. We argue that all extant fire regimes, in a sense, are anthropogenic and understandings of human agency, knowledge and the history of social systems are essential for characterising contemporary and historical fire ecology.

Human agency and decision-making

Only recently have researchers begun to systematically explore the role of human agency on the landscape with regards to fire ecology (Anderies *et al.* 2002; Laris 2002; Bird *et al.* 2005; Kepe 2005; Mistry *et al.* 2005). Agency and intentionality are significant for fire ecology because at the scale of individuals, social and biophysical processes clearly interact to form emergent human–fire ecologies. In contemporary social theory, social groups and their cultures embody the interactions of individuals (Ortner 1984; Smith and Boyd 1990; Brumfiel 1992). Links among and between individuals and institutions are often modelled as network phenomena (Borgatti *et al.* 2009) that interact via cross-scale and cross-level linkages embedded within dynamic and complex systems (Cash *et al.* 2006). The term 'agency' refers to an individual's 'socioculturally mediated capacity to act' (Ahearn 2001) within those systems.

It is sufficient for our purposes to state that in recognising human agency, we open up the possibility for understanding human–fire relations in the context of cognitively intentional behaviour resulting from decision-making processes. Human–fire–landscape interactions are most conspicuously related to human agency through the timing and placement of ignitions. However, wherever the explicit purpose of human behaviour is not directed towards specific fire ignitions, human agency is

nonetheless inextricably tied to resulting fire spread through historical processes, particularly the influence of humans on landscape structure (Christensen 1989).

Agency and ignition

Decision-making processes are integral components of a causal explanation of ignition patterns. Calculated timing and placement of ignitions represents the simplest and most efficient way to influence fire patterns (Granstrom and Niklasson 2008). In order to control or contain a landscape fire, the decision of when and where to start the fire requires premeditated consideration of complex ecological processes (Lewis 1978). If people lack sufficient understanding of fire cause and effect, the resulting flawed decision-making leads to unintentional ignitions. Where qualitative understanding of decision processes is impossible, for example in historical contexts, fire-use and management rationale must be inferred from available historical and archaeological evidence.

Agency and spread

Causes of ignition have received undue attention in many previous analyses of wildfire (Vayda 2006). The focus on ignitions at the expense of causes of spread reflects an ahistorical outlook. It is the interaction of ignitions with historically contingent vegetation types and conditions that actually defines a fire event. Humans frequently manipulate fuels with the intent to change fire behaviour and thus fire spread. Modern fuel-management activities can involve active manipulation of fuels during the fire event, as in wildland fire suppression, or in anticipation of fire events, as in the construction of a fire break. On the other end of the spectrum of intent, land-use consequences represent previous human activities that have altered the landscape in some way. For example, fire suppression itself (Minnich 1983; Donnegan *et al.* 2001; Heyerdahl *et al.* 2001), logging (Franklin and Forman 1987; Whitney 1987), the introduction of invasive species (D'Antonio and Vitousek 1992; Setterfield *et al.* 2010), grazing (Madany and West 1983; Savage and Swetnam 1990) and agricultural land abandonment (Lloret *et al.* 2002; Moreira and Russo 2007) all have both immediate and lasting consequences for fire behaviour.

Historically fire ecology has most often engaged with the anthropogenic causes of fire spread in order to explain shifts towards more catastrophic fires. In the United States, implications of fire suppression as a cause of 'wildfire hazard' in diverse regions helped establish the science of fire ecology (Green 1931; Chapman 1932; Stoddard 1935; Garren 1943; Weaver 1943; Cooper 1960; Hartesveldt and Harvey 1967; Kilgore 1973). Much of this literature suggested a role for intentional fire use in managing forests and fire, citing historical fire-use practices as evidence for its utility (Komarek 1962; Stoddard 1962). In landscapes with sufficient histories of fire use as a land-management tool, land-use practices maintain patchworks of fire-adapted and fire-resistant land covers, thus determining fire spread (Fig. 2). Fire ecology has a need to better understand how human agency has contributed to sustainable fire management.

Knowledge and practice of landscape fire

If a discussion of agency allows us to understand the role of humans in ignition and spread, a discussion of the knowledge and practice of landscape fire can help us understand the cultural context and development of that agency. Ethnographic evidence overwhelmingly points to the intentional use of landscape fire by diverse cultures throughout human history and across a wide variety of the world's biomes. Just as humans have played a more significant role in initiating particular landscape fire events and regimes, the control of fire constituted an equally significant evolutionary factor for human subsistence behaviours and knowledge systems and for millennia has been intimately tied to such fundamental technological processes such as heating, cooking, clay firing, fire tempering in wood and stone tools, lime production for plaster, and metallurgical smelting (Pyne 1982, 1998). Broadcast fire is associated with hunting, plant tending (for food and fibre), pest management and fire prevention to name a few categorical uses (Lewis and Ferguson 1988; Anderson 1996; Head 1996; Russell-Smith *et al.* 1997; Mistry *et al.* 2005; Eriksen 2007). The role of fire use in the

Fig. 2. Land-use legacies, including the history of fire-use itself, serves to control fire spread. (*a*) Pastoral fires in the French Pyrenees have helped shape mountain landscapes for several thousand years. This late-winter surface fire burned south facing grasslands (*Brachypodium pinnatum*), but did not enter still green hay meadow surrounding barns (centre) nor did it penetrate forest patches despite topography and wind direction (view is east, wind direction south to north). Photo: M. R. Coughlan, 2011. (*b*) The Hagahai people of the interior lowlands of Papua New Guinea regularly burn upland areas to clear brush and flush out pigs. Over time, this cultural practice has generated a forest–grassland mosaic with tropical rainforest along moist drainage lines and kunai (*Imperata cylindrica*) grassland on upland areas. Photo: A. M. Petty, 1997.

development and spread of agriculture is thought to be significant, perhaps paramount (Conklin 1961; Lewis 1972; Naveh 1975; Boserup 1981; Clark 1989). To this effect, anthropogenic fire regimes reflect human fire practices, which are part of the broader fabric of human culture.

Acquisition and deployment: short- and medium-term process

Knowledge and practice of fire use is a dialectic process between humans and their environment. In addition to engaging the biophysical landscape, fire practices are also part and parcel of the production and reproduction of social relations, identity and the situated action of daily life. Prior to the intervention of state-based land management, fire-use knowledge was imparted through kinship and other cooperative labour networks in the context of land-based livelihood activities. Learning techniques like fire use and control can be understood as a process of 'enskilment' (Ingold 2001), where individuals learn to apply and adapt cultural knowledge to real-world situations through direct experience (cf. Berkes 1999; Berkes *et al.* 2000).

As a product of dynamic social relations, fire-use knowledge is sensitive to both bottom–up and top–down changes in social and ecological systems. Bottom–up changes, such as a demographic decline leading to the deterioration of cooperative labour networks, may negatively affect both the transmission of fire-use knowledge and the physical capacity to control fire spread (Métailié 2006). Where opportunities to practice fire use become constrained from the top–down, for example governmental policies enforcing fire exclusion, cultural knowledge of fire ecology also risks degradation. A study of fire suppression history and social memory in Oaxaca (Mathews 2003) found that local peoples had 'forgotten' not only the fact that their ancestors used landscape fire, but that fire was ever a part of the forest ecology. Similar effects have been noted in Alberta (Ferguson 1979) and are likely to be true in the United States given the effectiveness of the Smokey Bear campaign and its ideological precursors (Dods 2002).

Evolution and adaptation: long-term processes

Given sufficient practice, fire-use knowledge and fire ecology may co-evolve. For example, in northern Australia, it is likely that the current pattern of extremely hot late dry-season fires results from a relatively recent (within the last 4000 years) climactic shift; such fires would have been less likely with or without human intervention a few thousand years ago. The Aboriginal ethic of early-season burning may have emerged as a response to this shift in seasonality. Thus, what developed was a relationship between humans and fire over millennia rather than simply the imposition of pre-adapted fire practices by Aboriginal hunter-gatherers (Head 1994*b*, 1996). Because traditional fire use often reflects a long-term historical dynamic between landscape, land use and knowledge accumulation, such fire-use knowledge may be extremely valuable in conservation and land-management contexts (Shaffer 2010).

Knowledge and practice as multidimensional link

Documenting the minute details of how people burn the landscape isn't merely a trivial or arcane ethnographic pursuit. Rather, such investigations provide important information for understanding the links between knowledge, socioeconomic systems and ecologically significant behaviours. But research and analysis of fire practices involve more than simply 'asking the locals' what they do. Ecological knowledge and practice provide a multidimensional link between human agency and broader socioecological processes. Research designs that seek to incorporate the knowledge and practice of fire use must account for the significance of social institutions, property regimes, cultural preferences, interpersonal and inter- and intra-ethnic politics, and how these things have changed through time.

History of social and ecological dynamics

In one of the first formulations of the ecosystem concept, Tansley (1935) argued for a system of ecological concepts applicable to both 'natural' conditions and those caused by human activity. Not long afterward, the study of human ecology emerged as scholars began to apply ecological theory and concepts to archaeological and ethnological problems (e.g. Steward 1955; Clark 1957). Over the last two decades, scholars have proposed a wide variety of approaches for integrating social and ecological systems (Crumley 1994; McGlade 1995; Gragson 1998; van der Leeuw and Redman 2002; Berkes *et al.* 2003; Barton *et al.* 2004; Redman *et al.* 2004; Balée 2006; Kohler and Leeuw 2007; Liu *et al.* 2007). Although each of these approaches presents slightly different perspectives on how best to integrate social and ecological history, they share the notion that social and ecological systems are inextricably linked through historical and reciprocal processes.

Social systems and human ecology

Theorists have long pointed out the relative importance of biophysical conditions and strategies of production for explaining the human condition and its relation to the environment through time (e.g. Malthus 1798; Darwin 1859; Marsh 1865; Marx and Engels 1987). One of the most important theoretical contributions from early human ecology studies concerns the idea that for humans, the constraining factor was not the environment, *per se*, but 'the manner in which it was exploited' (Steward 1938, p. 230). Human agency was inherent in the concept of adaptation as a 'creative process' (Steward 1955) where cultural innovations such as technology, social organisation and productive processes mediate how environmental parameters effect a population (Bettinger 1998). For example, a period of decreased precipitation may be experienced negatively by agriculturalists who fall back on smaller, irrigated plots where, under these same conditions, hunter-gatherers may expand their territory. Following similar logic, Boserup (1966) showed how human demographic pressures tended to promote land-use intensification and not population collapse (Malthus 1798). At the same time, social institutions and cultural practices associated with particular productive processes were found to help regulate demographic growth (Rappaport 1967; Netting 1981; Bettinger 1998). Studies of more complex societies yielded the insight that human–environment interaction isn't simply determined by isolated systems of production, but also external political and economic pressures, the division of labour and the differential access to and distribution of resources, material and intellectual (Wolf 1966, 1972, 1982), the totality of which we refer to here simply as social systems.

Much of the early work in human ecology touched on the subject of human fire use (Clark 1947; Sauer 1950; Stewart 1951; Conklin 1954; Geertz 1963), in part because fire-use practices form an important component of livelihood strategies in small-scale economies. Unfortunately, fire ecology research has largely ignored this literature and focuses instead on trying to establish more deterministic relationships between, for example, population density and fire frequency (Prentice 2010). The difficulty in distilling a relationship between population density and fire concerns the fact that fire does not result directly from the mere presence of humans. Ignitions result from human behaviour, whereas fire spread is determined by fuel load and continuity, which are in turn controlled by human land-use practice (Ehrlich *et al.* 1997) and land-use legacies. Although land use is closely tied with the relationship between population densities and land availability (Boserup 1966; Netting 1981), it is also modulated by environmental constraints (Turner *et al.* 1977), as well as institutions and economic factors (Lambin *et al.* 2001). Thus, as other scholars have shown (Guyette *et al.* 2002; Archilbald *et al.* 2008), the relationship between population density and fire is complex, variable and certainly not a simple linear equation.

The dynamic interaction of and changes within social systems are the direct link between human populations and land use (Lambin *et al.* 2001). From this perspective, anthropogenic fire regimes may be understood as the product of reciprocal interactions between social and ecological systems, often forming an integral component of land-use strategy. Such fire regimes, while both dynamic and open-ended, are subject to change or persistence in the system as a whole. We propose that wherever social systems of production and distribution shift, we are likely to see significant shifts in the anthropogenic fire regime and vice versa. In support of this hypothesis, we present two brief historical case-studies: the south-eastern United States and the tropical savanna region of Australia.

South-eastern USA

In the south-eastern United States, Delcourt and Delcourt (1998) show that subsistence intensification after 3000 years BP with the introduction of maize through the Woodland, Mississippian and Historic Native American period correlates with the increasing importance of fire-tolerant tree species such as oak and chestnut. Shifts in sedimentary charcoal show variability in fire regimes over this same time period (Delcourt and Delcourt 1997). The evidence implies a variable but gradual intensification of the use of fire by Native Americans. Following European colonial contact, fire frequency and extent appear to have increased, reflecting an intensification of hunting-associated fire use driven by the European demand for furs and hides (Foster and Cohen 2007).

European settlers also brought agropastoral fire practices with them from Europe and quickly adapted them to local conditions. Palaeoecological evidence shows that landscape fires in the south-eastern United States increased in tandem with the influx of European Americans along the frontier (Harmon 1982). Settlers used relatively infrequent clearance fires in shifting agriculture (Otto 1983) and frequent, sometimes annual, low-intensity fires in range management (Otto 1984). By the late 19th century, private timber companies gained control of vast tracts of forested land (Otto 1983), and the industrial logging operations that followed altered fire regimes from controlled, frequent and low-intensity ground fires to less predictable high-intensity conflagrations (Pyne 1982; Fowler and Konopik 2007). Slash left behind from logging operations provided the initial fuels for such fires whereas new technologies such as the railroad and new agents such as forestry workers provided additional ignition sources outside the conventional burning season. Fire suppression, initiated in the early 20th century, accompanied a wider regime of reforestation and land consolidation in the more agriculturally marginal areas. Burning became a clandestine practice (Shea 1939; Henson 1942). Following World War II, the combination of fire prevention and suppression programs with land-use changes such as road development, agricultural land abandonment and urbanisation (Gragson and Bolstad 2006) significantly reduced fire spread but did little to quell ignitions in the South. Today in North Carolina, for example, fires are generally smaller than in the past, but just as numerous (North Carolina Forest Service 2011; Fig. 3).

Despite these changes, intentional fire use clearly continues to play a role in the socioecological systems of the US Southeast. Since the 1940s, the highest number of human-caused fires in the US have occurred in the Southeast (Stephens 2005). In 2009, combined wildfire statistics for Alabama, Georgia and Mississippi show that 75% of wildfires were intentionally set, resulting in unauthorised burning: 37% were illegally set whereas 38% resulted from legally permitted fires that escaped their proposed boundaries (Alabama Forestry Commission 2010; Mississippi Forestry Commission 2010; Georgia Forestry Commission, unpubl. data, 2010; Fig. 4).

Tropical savanna region of Australia

The tropical savanna region of Australia is one of the most fire-prone regions on Earth, and one of the least populated. Fire management has always been an integral part of Aboriginal livelihoods (Jones 1969). European colonisation changed fire management substantially in the region. The manner of change, however, has diverged depending largely on geography and the predominant economic activity.

The region ~14–16°S in latitude is particularly suited to pastoral production, and following European settlement in the Victoria River District of the Northern Territory, the Kimberley region of Western Australia and western Cape York region of Queensland, Aboriginal fire management became intertwined with the needs and logic of the pastoral industry (Head 1994*a*, 1994*b*; Crowley and Garnett 2000). Although the outcome varied from region to region, in general the seasonality of 'acceptable' fire contracted significantly to accommodate cattle grazing. In Western Australia, fire was widely practised historically by both pastoralists and Aboriginal people, many of whom were the labour backbone of cattle stations. However, today pastoralists widely see fire as a threat (Head 1994*a*). By contrast, in north-eastern Queensland fire is still a significant component of cattle station management and even late-season 'storm burns' are used, albeit probably to a lesser degree than was historically the case, to reduce woody vegetation thickening (Crowley and Garnett 2000).

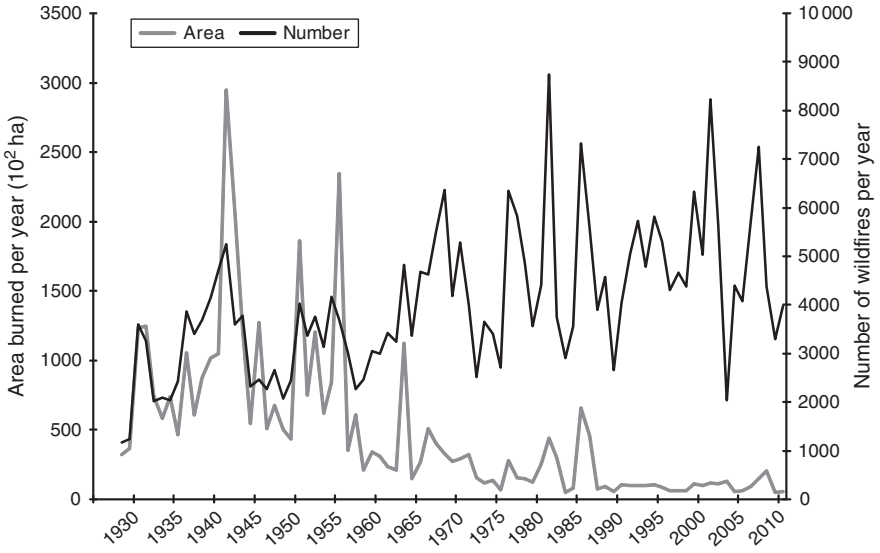

Fig. 3. Fire incidents in North Carolina, 1928–2007. A drastic decline in annual area burned accompanies an increase in number of fires. Average fire size from the most recent decade (1997–2007) had declined ~90% from the period 1928–1960 whereas the average number of fires increased by 40%. Data: North Carolina Forest Service (2011).

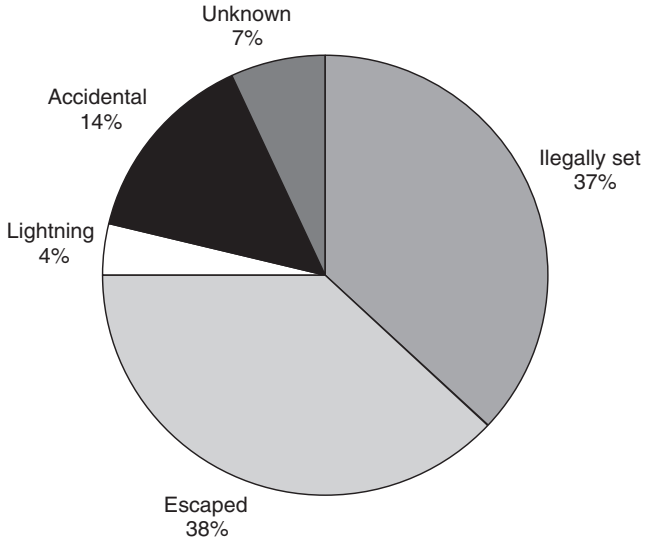

Fig. 4. Wildfires by cause in the US Southeast. Data: combined wildfire statistics for Alabama, Georgia, and Mississippi, 2009.

The northernmost regions of Australia's tropical savannas were much less suitable for cattle production, and there the most significant changes to fire regimes occurred as a result of the depopulation of Aboriginal communities due to death from disease, social dysfunction and migration to 'town camps' as Europeans and Chinese began extensively settling the region. Some regions lost 97% of their Aboriginal population in the wake of a gold rush in the late 1800s (Keen 1980). This left vast areas bereft of land managers. Fire regimes shifted from smaller, patchy fires occurring throughout the dry season to extensive fires occurring in the late dry season. The depopulation of Aboriginal land managers has been specifically linked to the decline in native species in the fire-regime-sensitive sandstone heath communities (Bowman and Panton 1993; Price and Bowman 1994; Russell-Smith *et al.* 1998). With some regional exceptions such as National Parks and settled regions of Aboriginal lands, a near-complete absence of land management persists across most of northern Australia (Russell-Smith *et al.* 2003; Russell-Smith and Edwards 2006).

Today, land managers across the tropical savanna region have institutionalised the practice of early dry-season burning as protection against late dry-season fires. This philosophy is based on European interpretations of Aboriginal fire-use practices but without regard to how often early-season burning was actually practised historically by Aboriginal people (Crowley and Garnett 2000; Preece 2002). In well-resourced regions such as Kakadu National Park, 300 km east of Darwin, early dry-season burning has resulted in both a dramatic turnaround in the seasonality of fires (Price *et al.* 2005) and an increase in fire frequency (Petty and Bowman 2007). By contrast, Aboriginal people in Arnhem Land adjacent to Kakadu ignite frequent fires throughout the dry season near settlements and roads, and less frequent but large fires further from roads and settlements (Petty and Bowman 2007). Today, access limits the number of ignitions in more remote areas, but before Aboriginal depopulation and increased sedentism, late-season Aboriginal fires were common across the landscape (Preece 2002).

This history has resulted in a three different systems of fire management across northern Australia (summarised in Fig. 5): (1) well-resourced regions where fire management is practised as hazard mitigation are strongly biased towards high-frequency, early dry-season fires; (2) pastoral properties have infrequent fires, typically early dry-season but sometimes late dry-season; and (3) Aboriginal tenure lands where fires occur frequently throughout the year near settlements and less frequently late in the dry season away from settlements.

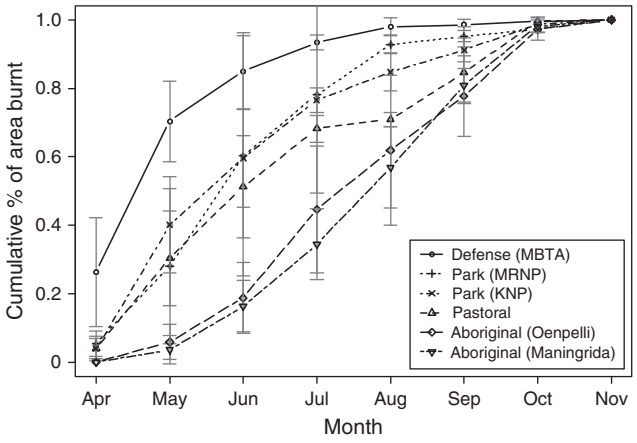

Fig. 5. Cumulative percentage of fires by area occurring within each dry-season month by tenure type, as determined from MODIS-derived fire-scar maps supplied by the Bushfires Council, Northern Territory. Values were calculated as the mean number of fires occurring within each month over a 4-year period (2002–05), in the northern savanna region of Australia, 150–400 km east of Darwin. Vertical bars show the interannual variability in percentage of fires occurring in each month as the standard deviation about the mean. The Mount Bundy defence training area (MBTA) and Kakadu National Park (KNP) are both highly resourced and intensively managed for fire. Mary River National Park (MRNP) is less well resourced, but with a similar fire-management mandate. The pastoral properties manage several hundred head of cattle. Oenpelli and Maningrida refer to two administrative districts within the Aboriginal freehold property of Arnhem Land. Complete data and methods are presented in Petty and Bowman (2007).

Discussion and conclusion: towards a transdisciplinary fire ecology

Even brief historical overviews can provide enough context to illustrate the ways in which major historical shifts such as colonisation, industrialisation and globalisation have affected contemporary fire regimes. Such histories also serve to steer fire management conversations away from the notion that historical or indigenous burning practices were somehow static, 'natural' or inherently ecologically beneficial (Krech 1999), or that European colonisation brought uniform and monolithic changes. To the contrary, the idea that culture alone drives land use and management is overly simplistic and fails to adequately capture ecologically important differences between the various types of anthropogenic fire and their practitioners.

What is universally significant about the processes of European colonisation, for example, concerns the fact that it marks a transition between social systems of production and distribution and, as with other transitions in history, this had a profound effect on fire ecology. As outlined above, early European settler-colonists may have used fire in much the same ways as indigenous peoples by following similar seasonal patterns or other environmental cues. They may also have used fire for similar reasons: agricultural land clearance, improving forage for game and livestock, pest management, etc. However, in comparison with their indigenous predecessors or neighbours, European colonists participated to a much greater degree in the steadily intensifying and globally integrating social systems. Given that fire use is one of the easiest and most widespread methods for increasing productivity because it saves on labour and capital (Boserup 1981), one would predict that the demands of colonial economies would have resulted in an increase in fire use. Indeed, an intensification of fire frequency coincident with the arrival of European colonists is consistent with palaeoecological evidence from Patagonia (Veblen *et al.* 1992; Whitlock *et al.* 2006), New Zealand (McWethy *et al.* 2009), south-eastern Australia (Haberle *et al.* 2006; Bickford *et al.* 2008; Fletcher and Thomas 2010), the eastern United States (Russell 1997; Parshall *et al.* 2003) and north-western California (Finney and Martin 1989). At the same time, the relationships between social systems and fire frequency are complex. In some contexts, increased fire frequency corresponding with shifts in the social system was a temporary aberration suggesting an initial phase of land conversion followed by a completely different fire regime. In other contexts, insufficient knowledge of appropriate burning seasons may have increased the frequency of escaped fires (Tacconi and Vayda 2006), or as the example from the tropical savanna region of Australia shows, in highly fire-prone biomes, the colonial transition may have promoted an overall decrease in anthropogenic fire, which did not have a great effect on fire frequency but did lead to a shift towards larger fires later in the dry season.

Changes in social systems, land use or fire-use practices may not always significantly affect fire frequency, especially at certain spatiotemporal scales such as those often employed in palaeoecological investigations. Our examples illustrate systems where human–fire dynamics are highly variable. Other studies have suggested that human effects on fire regimes in other systems may have been minimal (Moore *et al.* 1999; Vale 2002; Carcaillet *et al.* 2007). However, a preoccupation with a methodologically delimited definition of 'fire regime' such as fire frequency might lead to the erroneous conclusion that a population did not use landscape fire. Depending on the frequency and intensity of human fire practices, anthropogenic effects on fire regimes may or may not be visible in the palaeoecological record given the limitations of currently available research methods in sedimentary charcoal (Higuera *et al.* 2005) and dendrochronology (Swetnam *et al.* 1999; McEwan *et al.* 2007). Recognising that humans did not always have profound effects on fire frequencies should not preclude us from trying to understand the actual ways in which humans used fire, locating the scales at which anthropogenic fire-caused effects occur and discovering the specific social and ecological forces associated with particular burning regimes. An apparent lack of evidence for anthropogenic fire regimes in certain times and places may be explained through comparative investigations in the known diversity of human fire practices (e.g. Natcher *et al.* 2007). From a socioecological standpoint, it is equally important to understand why humans may not have altered fire regimes in particular times and places. Indeed, such understandings may point towards important social and ecological thresholds between sustainable land and fire use and degradation of particular environments.

This paper suggests that 'human dimensions' in the study of fire ecology must include a program for investigating the social life of landscape fire that incorporates human agency, traditions of fire knowledge and practice, and the historical dynamics of the socioecological systems. This program compels us to search for and explain human–fire relationships rather than to simply prove or disprove the effects of anthropogenic fire at particular

spatiotemporal scales. Reframing human 'effects on fire regimes' in terms of the capabilities of humans to reciprocally interact with the various parameters of a fire regime recognises that fire use has been an integral component of the human project of biocultural survival and reproduction. Finally, locating fire ecology within the history of dynamic socioecological systems allows contextual understandings of processes that adequately account for causal relationships between changes in social systems and fire regimes.

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