Planning for resilience: modeling change in human–fire interactions in the Alaskan boreal forest

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The development of policies that promote ecological, economic, and cultural sustainability requires collaboration between natural and social scientists. We present a modeling approach to facilitate this communication and illustrate its application to studies of wildfire in the interior of Alaska. We distill the essence of complex fire–vegetation interactions that occur in the real world into a simplified landscape model, and describe how equally complex fire–human interactions could be incorporated into a similar modeling framework. Simulations suggest that fire suppression is likely to increase the proportion of flammable vegetation on the landscape and reduce the long-term effectiveness of wildfire suppression. Simple models that test the consequences of assumptions help natural and social scientists to communicate objectively when exploring the long-term consequences of alternative policy scenarios.

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One of the greatest challenges facing ecology is to understand how regional systems can sustain important properties at times when they face directional changes in biophysical (Vitousek *et al.* 1997) and social factors (Berkes and Folke 1998). The complexity of the problem often leads to piecemeal solutions by climatologists, ecologists, anthropologists, or political scientists. However, viable solutions require a systems perspective that integrates processes across these disciplines (Nicolson *et al.* 2002). This is particularly important at regional scales, where management agencies are looking for solutions to enhance the sustainability of many elements that are important to society, including economic well-being, ecosystem goods and services, and cultural integrity. Implementation of these goals requires a framework that incorporates human activities as an integral component of social–ecological systems, rather than an external force that modifies natural processes (Berkes and Folke 1998). Rapid development and testing of simple whole-system models that contain ecological, economic, political and cultural variables provides one way of exploring regional resilience (Carpenter *et al.* 1999). Here, we illustrate this approach using vegetation–fire–human interactions in the Alaskan boreal forest.

In a nutshell:

- To enhance regional sustainability we must consider human activities as integral components of social–ecological systems
- Rapid development and testing of simple whole-system models allows us to understand potential policy impacts on regional sustainability
- Simulations suggest that the short-term effect of fire suppression in interior Alaska is to reduce the annual area burned
- However, over the long term this leads to a higher proportion of flammable vegetation and an increased probability of fires near communities
- It is essential to integrate the natural and social sciences when evaluating the extent of potential human impacts on future fire regimes

The problem

The mosaic of ecosystem types in the Alaskan boreal forest is strongly influenced by fire. Black spruce (*Picea mariana*) forests and sphagnum bogs (muskegs), which occupy 40% of interior Alaska (Yarie and Billings 2002), are highly flammable, with fires occurring, on average, every 30 to 60 years (Yarie 1981; Van Cleve *et al.* 1991; Figure 1). The mean annual temperature of interior Alaska has increased by 2°C in the last four decades (Keyser *et al.* 2000), a rise as rapid as anywhere on earth (Serreze *et al.* 2000). This has nearly doubled the annual area burned in western North America in the last 20 years (Murphy *et al.* 2000). Warming has also increased drought stress in white spruce (*P glauca*) forests, reducing growth (Barber *et al.* 2000) and triggering widespread bark beetle outbreaks in southern Alaska (Holsten *et al.*

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Figure 1. *Wildfire in a black spruce forest of interior Alaska.*

1995), which also increase the chances of fires. If high-latitude warming continues as projected (Ramaswamy *et al.* 2001), fire may occur more frequently in the interior part of the state, with widespread ecological and societal consequences (Stocks *et al.* 2000; Flannigan *et al.* 2001).

People have always affected, and been affected by, fire in the Alaskan boreal forest, but the nature of this interaction is changing (Lutz 1959). Indigenous peoples used fire at strategic times, in selected areas, and under optimal conditions to influence the relative abundance and distributions of natural resources and wildlife species (Natcher in press). During the early part of the 20th century, a pulse of wildfire near gold-bearing creeks (Fastie *et al.* in press) probably reflected an increase in anthropogenic ignitions (Graves 1916). The overall human impact on the Alaskan fire regime has been relatively small, accounting for approximately 10% of the total area burned, (Kasischke *et al.* in press), and is concentrated near areas where people live (Gabriel and Tande 1983).

It has never been feasible to fully implement the federal fire policy (Pyne 2001) of suppressing all wildfires in Alaska. An Alaskan fire-management policy established in 1991 formalized an earlier pragmatic pattern of suppressing fires near populated areas and allowing them to burn in unpopulated regions. The change in human–fire interaction from enhancement to suppression could reduce the area burned near population centers, as has occurred in the continental US (Pyne 2001), although this has not been systematically studied in Alaska. We hypothesize that, over the long term, management policies that suppress fires close to communities increase the proportion of late-successional flammable vegetation on the landscape, eventually increasing the likelihood of future fires with relatively greater societal impacts.

■ Modeling complex regional systems

In this paper, we outline a modeling approach whose goal is to develop plausible scenarios of future changes in Alaska's fire regime, so fire managers recognize the long-term consequences of alternative fire policies. We have not yet designed this whole-system model, so here we describe our modeling approach using an existing model (ALFRESCO) of fire–climate–vegetation interactions (Starfield and Chapin 1996; Rupp *et al.* 2002), in order to frame questions regarding human–fire interaction in the same way in which a vegetation model was used to explore fire policies that enhance the resilience of rangeland grazing systems in Australia (Anderies *et al.* 2002). Our objective is to explore the impact of human activities on the short- and long-term frequency and extent of fire, a key issue in fire management.

Starting with this objective in the complex "real world", we deliberately design a "model world" that simplifies those parts of the "real world" that we choose to include (Figure 2). The decision on what to include should be guided only by the objective. Once the model world is designed, we construct a model and run it, using the best available data or best guesses at unavailable data. The results tell us something about the model world, not the real world. We then interpret these results (in the light of our assumptions) and draw tentative conclusions about the real world.

It is never easy, especially in an interdisciplinary project (Nicolson *et al.* 2002), to decide what to include in the model world. A common bias is towards inclusion rather than exclusion, for fear of oversimplifying. This bias is counterproductive. Instead, an approach of rapidly developing and testing prototype models is preferable (Schrage 1999). The goal of the first prototype is to complete the modeling loop, as simply and quickly as possible, (Figure 2), starting with the real world objective and ending with interpreted results. Once the loop has been completed, we can evaluate whether the modeling approach in the first prototype is useful. If not, we start again; otherwise we assess the sensitivity of our conclusions to the input data and to the assumptions that determined the model structure (Beres and Hawkins 2001). This leads to the design of the next prototype.

Rapid development of prototype models facilitates the construction of a simple model that abstracts the most essential features (in terms of having a strong influence on fire) of each component of the system (Figure 2). The resulting prototype is only a facsimile of reality, but it provides a framework for communication across disciplines, a focus for interdisciplinary hypotheses, and an objective criterion for deciding which processes to include in the model. Simplifications are necessary in going from the real world to

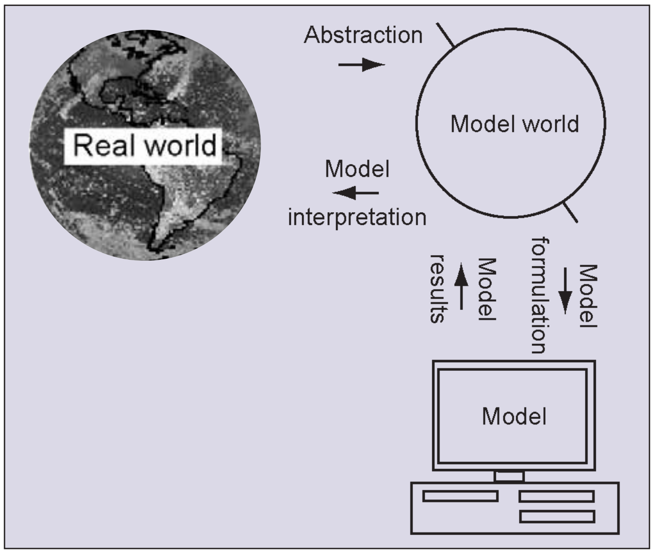

Figure 2. Relationships between the real world, the model world, and the model. The model world is an abstraction that includes only some of the structural and dynamic complexity of the real world. The model is an explicit description of the formal relationships between components of the model world. Model results describe the logical consequences of these model-world relationships. These results can be interpreted with respect to observations in the real world, through a careful comparison of the assumptions of the model world and hypotheses about how the real world functions.

the model world, as is encoding these simplifications into a model of fire–vegetation interactions or a future whole-system model of human–fire–vegetation interactions (Figure 3).

■ From the real world to the model world

Interactions between fire, vegetation, and climate

Climate governs fire on multiple time scales through its effects on fire weather (wind, temperature, humidity), fuel moisture, vegetation composition, and forest-floor depth (Johnson 1992). In an average year, the fire season in Alaska lasts only 3 weeks, from mid-June to early July, and very little land area burns. This fire season is sandwiched between early summer, when the surface organic mat is still wet from snowmelt, and late summer, when increased precipitation raises fuel moisture and atmospheric humidity to levels that do not sustain fire (Kasischke *et al.* in press). Most fires occur in "unusual" years (typically 2 or 3 per decade), when conditions remain dry through July or August (Kasischke *et al.* 2002; Murphy *et al.* 2000). Thus, although the climatic effects on ignition and fire spread are difficult to predict in the real world over short time scales, we can simplify them in our model world, using an empirical relationship between a drought index and annual area burned (Starfield and Chapin 1996; Rupp *et al.* 2002; Figure 4).

Vegetation effects on fire regime are just as pronounced as those of climate. Charcoal density, a measure of fire frequency, increased dramatically in Alaska 6000 years ago when black spruce became widespread, even though this coincided with a shift to a cooler, moister climate that was less conducive to fire (Lynch *et al.* in press). Black spruce forests are flammable because of the thick forest floor of detritus, an understory of resinous evergreen shrubs, a moss layer that dries rapidly, and resinous ladder-like fuels (Van Cleve *et al.* 1991; Johnson 1992). Although the mechanisms are complex, the increased flammability that occurs during succession can be described in the model world through a flammability coefficient that changes with vegetation type and stand age (Starfield and Chapin 1996; Figure 4).

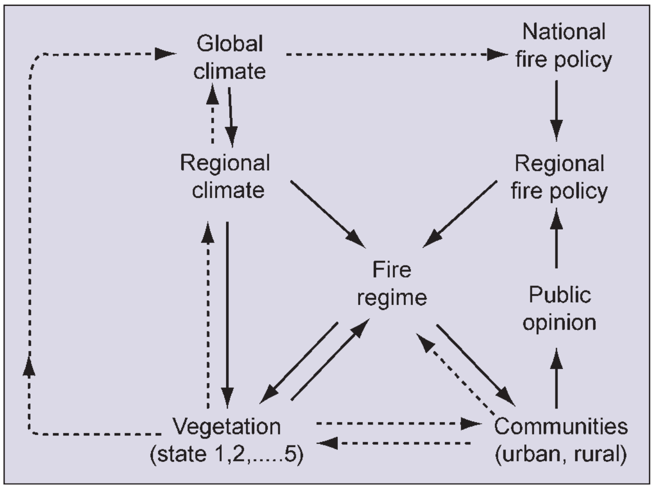

Figure 3. Conceptual model of interactions between climate, vegetation, fire, and human activities at the regional scale. Solid arrows indicate interactions to be included in the first prototype of the regional model. Dashed arrows indicate other interactions that may warrant consideration in later prototypes.

Vegetation also influences fire probability indirectly, through its effects on regional climate. Early-successional deciduous stands absorb and transfer only half as much radiation to the atmosphere as do late successional spruce forests (Baldocchi *et al.* 2000; Chambers and Chapin in press). Consequently, fire-induced increases in the proportion of deciduous forests on the landscape have a net cooling effect on climate, which should in turn reduce fire probability (Chapin *et al.* 2000). We currently ignore this climate feedback, but we could vary the magnitude of climate feedbacks to explore whether our model is sensitive to them. Based on these tests, we could decide whether or not to incorporate such feedbacks into future versions of the model.

Lightning is the major natural ignition source in interior Alaska (Gabriel and Tande 1983; Dissing and Verbyla in press). Most strikes do not produce large fires because they occur when fuel moisture, relative humidity, and/or temperature are unsuitable for fire. During one 3-year prescribed-fire study in interior Alaska, for example, conditions were suitable for ignition for only one week (Hinzman *et al.* in press). We believe that lightning ignition varies stochastically from year to year, and treat geographic variation in ignition probability as a component of climate (Starfield and Chapin 1996).

In summary, despite the complexity of fire–climate–

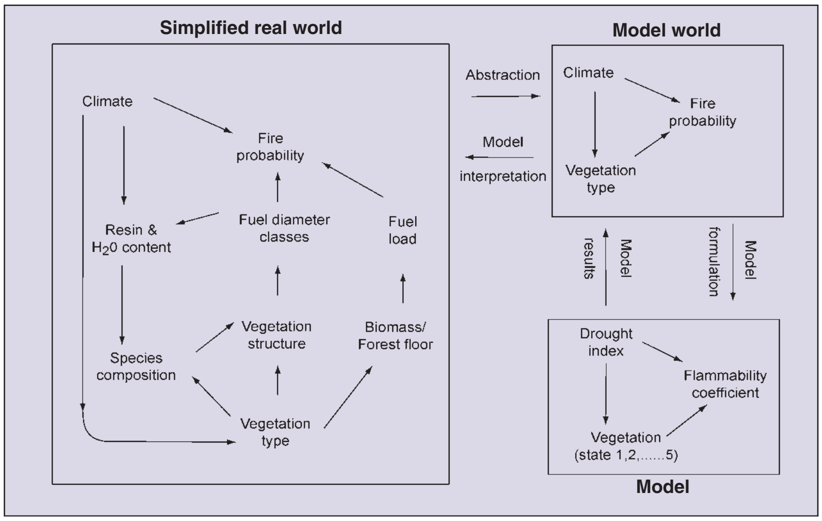

Figure 4. *Relationships between fire, vegetation, and climate in a simplified view of the real world, the model world, and the model. The current model (ALFRESCO) consists of a grid of interacting cells, each of which has a specified vegetation type, age, and climate. In the short term, fire number and size depend primarily on vegetation and climate. Over the long term, fire also depends on feedbacks from fire regime to the relative proportions and spatial patterns of vegetation on the landscape (Rupp* et al. *2000). Complexity and uncertainty are incorporated in the model through stochastic cause-and-effect relationships.*

vegetation interactions in the real world, the model world recognizes only a few factors that account for large interannual variations in fire size and number (Figure 4).

Human–fire interactions

People directly affect fire regimes through ignitions, fire suppression, and vegetation modification. We cannot currently separate the effects of indigenous people on fire frequency (Baker and Ehle 2001; Natcher in press) from those of climate and vegetation when we reconstruct fire probabilities from the frequency distribution of stand ages (Yarie 1981). We therefore incorporate Native American burning as a component of the natural fire regime in our model and do not explicitly model it.

Human activities accounted for 62% of the fires in Alaska from 1956 to 2000, but only 10% of the area burned (Gabriel and Tande 1983; Kasischke *et al.* in press), because most fires are lit in places where, or at times when, the landscape is not highly flammable. Campfires, for example, which account for 30% of human-caused wildfires, are more often lit in riparian zones dominated by deciduous vegetation than in flammable black spruce forests. Similarly, land clearing and construction, which account for 20% of anthropogenic fires, are concentrated in well-drained habitats with vegetation that burns less readily than lowland black spruce (Gotholdt 1998). Moreover, areas that are accessible to people who ignite fires are also accessible to fire fighters who put them out. Because the geographic pattern of fire ignition is similar to that of suppression, our first prototype model of human impact on fire regime considers human impact as a single process that alters fire frequency and extent. Fire suppression has a greater effect on area burned than human ignitions, so inhabited areas generally have more fires but less area burned than do areas with a more natural fire regime (L DeWilde unpublished). We could test the importance of including human ignitions as a separate process (Anderson *et al.* 2000) in a second prototype model, using maps of observed patterns of human ignition (Figure 3).

The impacts of fire on society depend on the type of human community and the time scale considered. The greatest short-term societal impacts are the risks to life, property, forest resources, and health (smoke inhalation). The spread of residences across the landscape increases fire probability (Pyne 2001). Fire also has short-term positive effects that accrue primarily to rural residents. Firefighters' wages account for up to 50% of the annual cash income in many rural villages. This income sustains populations and subsistence traditions in Athabascan villages where there is 50–90% unemployment and few alternative income sources. Native groups are outspoken advocates for fire suppression, presumably because of the substantial risks to life and property in remote areas and the economic benefits that come from fire fighting. We intend to model the effects of fire on society by considering two types of community, urban and rural, which differ in the risks, benefits, and ecosystem services resulting from fire, and therefore differ in opinions about the desirability of fire suppression (Figure 5).

The long-term effects of fire on society depend on the changes in ecosystem services that result from fire. Early successional vegetation supports mushroom production for 2–4 years after fire, berries for 2–20 years after fire, and moose and furbearers between 10 and 30 years after fire. Conversely, firewood and timber products are reduced for 30–50 years after fire. The less flammable deciduous vegetation that develops after fire reduces fire risk to adjacent property owners for about 30–60 years in black-spruce-dominated lowlands and for about 80–100 years in white-spruce-dominated uplands (Van Cleve *et al.* 1991). We will develop alternative model scenarios in which these long-term effects have no impact (the current model structure) or strong impacts on public opinion (Figure 5).

Public opinion can affect the magnitude and distribution of fire suppression effort in several ways. The national policy of extinguishing all fires has remained uninfluenced by public opinion since 1910 (Pyne 2001). Because there are not enough resources to apply this policy to all of Alaska, the state's Wildland Fire Management Plan specifies a map that designates the level of suppression that each land unit should receive. Although managers can modify suppression classifications each year, they seldom do so, suggesting that public opinion has little impact on policy formulation.

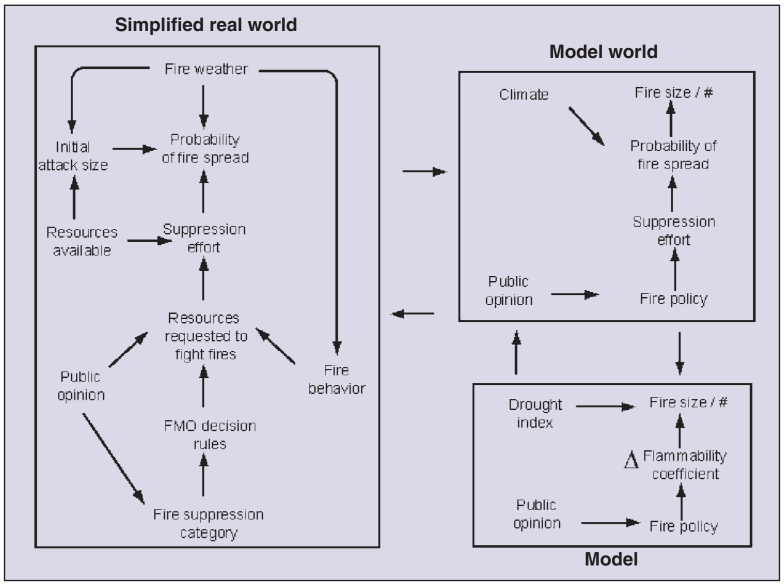

Figure 5. *Relationships between human activities, fire policy, and fire in a simplified view of the real world, the model world, and the model. In the model, national fire policy is treated as a constant that defines the rules by which suppression activities should be implemented. These rules are converted into a geographically explicit fire policy that designates a map of suppression categories. The net effect of suppression is a reduction in the vegetation-specific flammability coefficient, which influences fire probability and the ease with which fire spreads to adjacent grid cells*

The Fire Management Officer (FMO) responsible for managing a specific fire decides the number of people and quantity of equipment necessary to achieve the goals of the fire management plan. Vocal concerns from local residents can influence these requests, suggesting that public opinion has a strong influence on local implementation of fire policy. The resources requested by an FMO are usually provided, unless the total requests for the region exceed the available resources. Fire suppression efforts have variable success, depending on resource availability, fire size, and weather. We simplify these complexities in the model world by designating fire policy as a map of suppression categories, whose implementation is modified randomly by public opinion (Figure 5).

Despite the complexity and unpredictability of societal and institutional responses to fire, then, the model world recognizes several generalized avenues by which public opinion responds to and affects fire regime through fire policy (Anderies *et al.* 2002; Figure 3). We can test the consequences of changes in the opinions of managers or local residents on fire regime by altering the rules or strength of the feedback pathway between policy, fire, and community.

■ The impact of policy on fire regime

As a preliminary test of potential human impacts on the Alaskan fire regime, we used ALFRESCO, a spatially explicit landscape model of fire–vegetation interactions, to explore whether human-induced changes in probability of ignition and fire spread would alter vegetation and fire regime over the long term. To simulate the effects of fire suppression, we reduced by either 25% or 50% the probability that large (≥ 1 km^2) fires would occur and spread to adjacent pixels (Figure 6).

In the test, we simulated five scenarios in which the parameters that govern probability of fire ignition and spread were altered to values ranging from 50% greater to 50% less than values that have been calibrated to reproduce the current fire regime of Alaska (Rupp *et al.* 2002). In each scenario, the same percentage change was applied to all vegetation types in the model. The current fire regime of Alaska was averaged across an area in which human ignitions account for less than 10% of the area burned. Simulations that increase flammability could represent increased human ignitions or ecological changes caused by a continuation of recent warming trends (Keyser *et al.* 2000). Simulations that reduce the probabilities of ignition and spread represent the effect of fire suppression on the number and size of large fires (≥ 1 km^2) and resulting changes in vegetation. Simulations were conducted on a map of current vegetation and climate in a 43 700-km^2 region of interior Alaska (centered on 65°N, 147°W), between Fairbanks and the Yukon River.

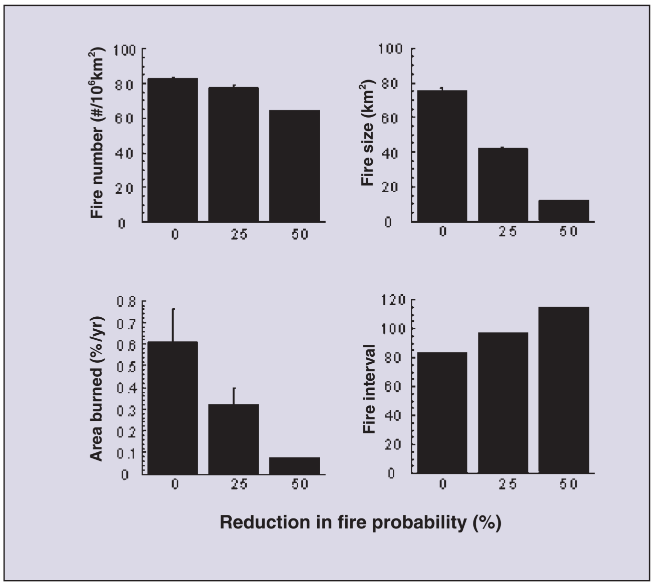

Figure 6. *Effect of fire suppression (either 25% or 50% reduction in the probability of fire and fire spread) on fire number, fire size, total area burned, and interval between successive fires. Data are means and standard errors of the means of 20 replicate simulations. We used a new version of ALFRESCO that operates on finer time scales (annual) and spatial scales (1 x 1 km) than the original model (Rupp* et al. *2000, 2002) because these scales are more appropriate to the interaction of fire policy and fire regime. Individual replicate runs showed much larger interannual variation in area burned.*

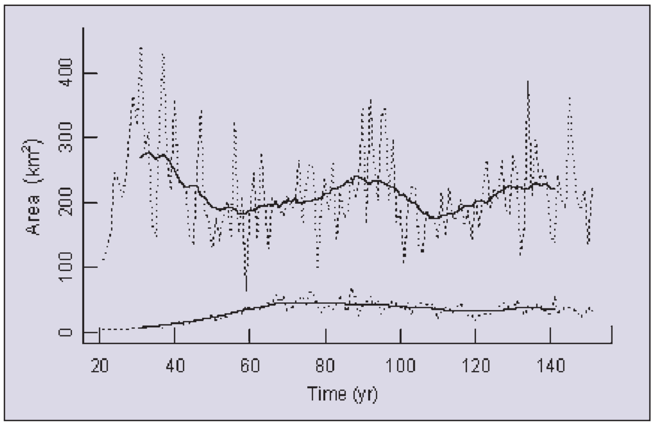

Figure 7. *Time course of annual area of black spruce burned in control simulations and in simulations in which fire probability was reduced by 50%. Total area of the region is 43 700 km^2, and "time" is the number of years after initiation of the fire suppression regime. Dashed lines are the annual means of 200 replicate simulations. Solid line is a 20-year running mean.*

The 50% reduction in fire probability caused a modest (22%) reduction in the number of fires and a large (6.5-fold) reduction in average fire size. Together these changes in fire regime reduced the annual area burned eightfold and increased the fire return interval in the most flammable vegetation type (black spruce) from 83 to 115 years. When we altered vegetation flammability over a larger (2.7-fold) range, fire regime changed in ways that were similar in pattern but greater in magnitude than the previous results.

When fire suppression (a 50% reduction in the probability of fire and fire spread) was maintained for 150 years, the proportion of late-successional vegetation (black and white spruce forest) increased by 50–60%, and the proportion of early successional deciduous forest declined sevenfold. These changes in vegetation composition led to a sixfold increase in the area of black spruce burned between 30 and 70 years after the initiation of fire suppression, whereas the control run showed no consistent trend in areas where black spruce were burned (Figure 7). This suggests that the short-term effectiveness of fire suppression in reducing burned area declines over time, because of succession to a more flammable vegetation type. Managers cannot therefore extrapolate their current success in fighting fires into the future. However, even after 70 years, simulations representing fire suppression experienced less fire than did those with a natural fire regime.

■ Conclusions

The ALFRESCO simulations suggest that a suppression effort that generates a 25–50% reduction in the probability of 1-km^2 fires or of fire spread to neighboring grid cells could dramatically reduce the annual area burned, primarily by reducing fire size. The effectiveness of a given level of fire suppression declines with time in the model world, because the landscape becomes increasingly occupied by flammable vegetation. The large magnitude of suppression effects and their changes over time suggest that we need further modeling of the interactions between people, fire, and vegetation. Such a model might explicitly consider factors such as regional fire policy and cultural, demographic, and socioeconomic change.

How do these results compare to actual, observed human effects on fire regime? At first glance, the modeling results provide a reasonable match. Fire suppression applied to half the area near Fairbanks reduced the area burned fourfold (L DeWilde unpublished), suggesting that the eightfold reduction in area burned due to simulated fire suppression is plausible. In the model world, however, fire suppression universally reduces the probability that any grid cell will burn or that a fire will spread to adjacent grid cells. In reality, the effectiveness of suppression depends on how accessible a fire is to fire fighters, whether and how aggressively managers attempt to suppress a fire, the fire size at the time of attack, fire weather, etc. These factors should be explored in future prototypes.

Our results are consistent with the hypothesis that the increased frequency of large fires in recent decades in the western US could, in part, reflect a century of fire suppression. Extensive fires occurred in 2000 and 2002, despite improved technology and monumental efforts to suppress them (Pyne 2001). Our results also suggest that the development of models of vegetation–fire–human interactions could address regional questions of societal importance. For example, what are the short- and long-term costs and benefits of policies that promote fire prevention as compared to management using prescribed burns? Under what circumstances, over what time scales, and for which segments of society do the positive effects of fire on wages and ecosystem goods and services outweigh the negative effects? Under what institutional arrangements (ie model assumptions) could the long-term positive effects of fire be maximized and the negative effects minimized? What trajectories of fire policy, settlement policy, or socioeconomic and cultural variables might affect future fire regime? How might changes in fuel accumulation within a vegetation type as a result of fire suppression influence fire regime? This effect of suppression may be less important in Alaska than in the Intermountain West, so policies developed elsewhere may not be directly transferable to Alaska.

Questions such as these show that further progress in understanding the interactions between people, vegetation, and fire requires active collaboration between natural and social scientists, to assess the effects of fire on life, property, wages, and the provision of goods and services. Modeling acts as a vehicle for the interdisciplinary communication that is essential to place these issues in a common framework, thereby helping in the development of policies to sustain important goods and services for future generations.

Acknowledgements

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