Matthew L. Brooks

Chapter 3:
Plant Invasions and Fire Regimes

The alteration of fire regimes is one of the most significant ways that plant invasions can affect ecosystems (Brooks and others 2004; D'Antonio 2000; D'Antonio and Vitousek 1992; Vitousek 1990). The suites of changes that can accompany an invasion include both direct effects of invaders on native plants through competitive interference, and indirect effects on all taxa through changes in habitat characteristics, biogeochemical cycles, and disturbance regimes. Effects can be far-reaching as they cascade up to higher trophic levels within an ecosystem (Brooks and others 2004; Mack and D'Antonio 1998).

Direct interference of invaders with native plants can be mitigated by removing or controlling the invading species. In contrast, when invaders cause changes in fundamental ecosystem processes, such as disturbance regimes, the effects can persist long after the invading species are removed. Restoration of native plant communities and their associated disturbance regimes may be necessary to restore pre-invasion landscape conditions. In this chapter, I describe ways in which invasions by nonnative plant species can change fuel conditions and fire regimes, and discuss what can be done to prevent or mitigate these effects.

Fire Behavior and Fire Regimes

Fire behavior is described by the rate of spread, residence time, flame length, and flame depth of an individual fire (chapter 1). This behavior is affected by fuel, weather, and topographic conditions at the time of burning. Individual fires can have significant short-term effects, such as stand-level mortality of vegetation. However, it is the cumulative effects of multiple fires over time that largely influence ecosystem structure and processes. The characteristic pattern of repeated burning over large areas and long periods of time is referred to as the fire regime.

A fire regime is specifically defined by a characteristic type (ground, surface, or crown fire), frequency (for example, return interval), intensity (heat release), severity (effects on soils and/or vegetation), size, spatial complexity, and seasonality of fire within a given geographic area or vegetation type (Sugihara and others 2006b; chapter 1). Fire regimes can be described quantitatively by a range of values that are typically called the "natural range of variation" or "historical range of variation." The term "natural" requires a value judgment that can be interpreted in many different ways, and the term "historical" requires a temporal context that is often poorly understood, as does the term "presettlement" (chapter 1). Any of these concepts may be inappropriate as a reference set for management decisions if conditions have changed so much that the landscape cannot support a fire regime that is either natural or historical. The term "reference fire regime" is used in this chapter to describe a range of fire regime conditions under which native species have probably evolved, or which are likely to achieve specific management objectives such as maximizing native species diversity and sustainability. Current patterns of fire regime characteristics can be objectively compared to reference conditions, and shifts outside of the reference range of variation can be used to identify "altered" fire regimes.

Biological and Physical Factors that Affect Fire Regimes

Fire regimes are influenced by topographic patterns, climatic conditions, ignition sources, and fuels (fig. 3-1). Topographic factors are extremely stable at the scale of thousands to millions of years. Climate factors are relatively stable at the scale of hundreds to thousand of years, although rapid changes have occurred during the 1900s due to anthropogenic influences on the atmosphere (Houghton and others 1990). Ignition rates from natural sources such as lightning are related to climate and have a similar degree of stability. However, ignition rates from anthropogenic sources are related to human population levels, which can increase dramatically at the scale of tens to hundreds of years. In contrast, fuels are created by vegetation, which can change over a period of days to weeks due to land cover conversion to agriculture, some other human use, or other disturbance. Vegetation can also be changed over a period of years to decades due to plant invasions that can displace native vegetation and change fuel properties. Thus, alterations in anthropogenic ignitions and vegetation characteristics are the two primary ways in which fire regimes can change rapidly. In this chapter, I focus on fire regime changes due to vegetation changes caused by plant invasions.

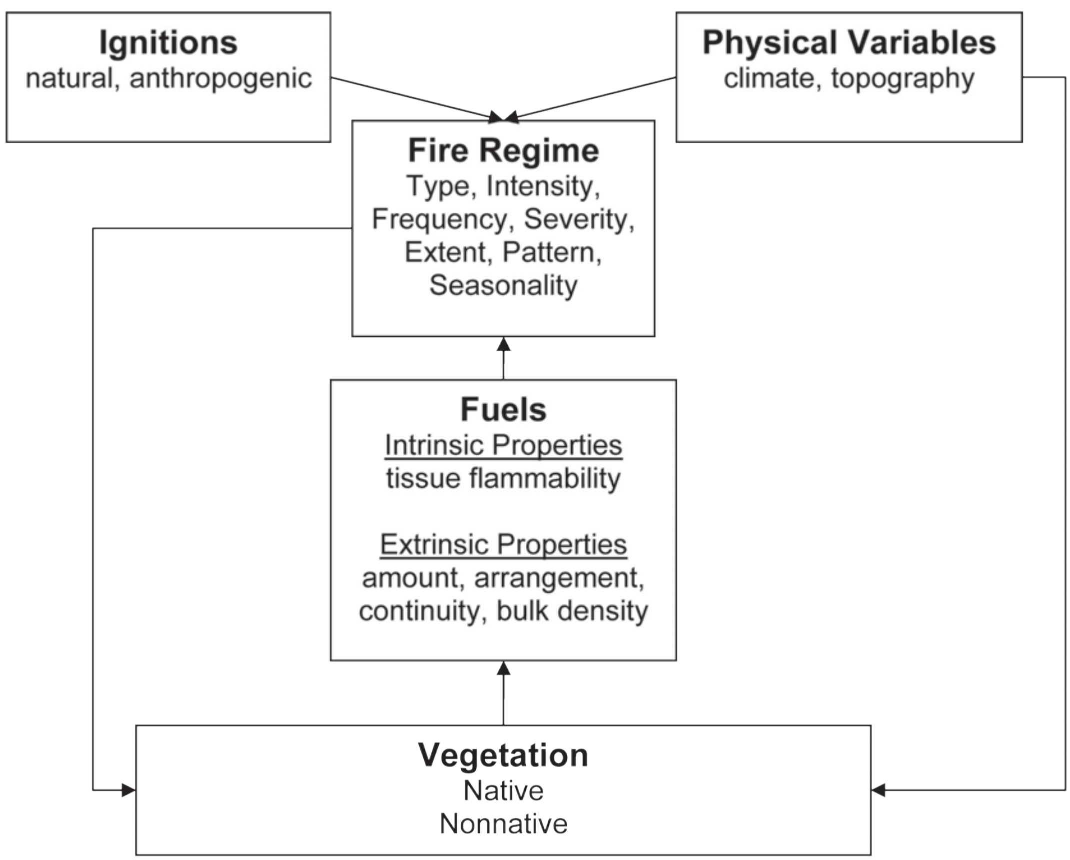

Figure 3-1—Biological and physical factors influencing fire regimes.

Effects of Plant Invasions on Fuels

Fuels can be classified into layers based on their vertical arrangement on the landscape. The fuel layers typically used to describe fire spread are ground, surface, and canopy fuels (chapter 1). Since plant invasions are less likely to alter ground fuels (organic duff and peat layers) in most ecosystems, surface and canopy fuels are emphasized in this chapter.

Surface fuels are typically dominated by litter plus herbaceous plants and shrubs, comprised mostly of fine (1-hour timelag: <0.25 inch (<0.6cm)) and medium-size (10-hour timelag: 0.25 to 1 inch (0.6 to 2.5cm)) fuels (Deeming and others 1977). In forested ecosystems, coarse (100-hour timelag: 1 to 3 inches (2.5 to 7.5 cm)) and larger diameter surface fuels may also be plentiful. Horizontal continuity of surface fuels is generally high in productive ecosystems such as riparian zones but may be very low in low-productivity ecosystems such as desert uplands (fig. 3-2).

Canopy fuels include fine to very coarse fuels, have low to high horizontal continuity, and have relatively low ignitability. The vertical spread of fire from surface to canopy fuels often requires ladder fuels that provide vertical continuity between strata, thereby allowing fire to carry from surface fuels into the crowns of trees or shrubs (fig. 3-3). Ladder fuels help initiate crown fires and contribute to their spread (National Wildfire Coordinating Group 1996). They may consist of vines or be comprised of the tallest surface fuels and the shortest canopy fuels at a given site.

In addition to fuel particle size and the horizontal and vertical distribution of fuel layers, other extrinsic fuel properties related to the way fuels are arranged on the landscape can influence fire behavior (fig. 3-1; table 3-1). The amount of fuel, or fuel load, primarily affects the intensity of fires. The fuel bed bulk density, or amount of fuel per unit volume of space, affects the rate of combustion, which influences the frequency, intensity, and seasonal burning window of fires. These properties also affect residence time and the

Figure 3-2—(A) High horizontal fuel continuity created by the nonnative grasses ripgut brome (*Bromus diandrus*) and cheatgrass (*Bromus rubens*) in a southwestern riparian ecosystem. (B) Low horizontal fuel continuity in a native Mojave Desert shrubland. (Photos by Matt Brooks, USGS, Western Ecological Research Center.)

Figure 3-3—High vertical continuity (ladder fuels) created by the nonnative giant reed (*Arundo donax*) in a southern California riparian woodland. (Photo by Tom Dudley, UC Santa Barbara.)

Table 3-1—Primary effects of fuelbed changes on potential fire regimes.[a]

Fuelbed change	Fire regime change
Increased amount (load)	Increased fire intensity and seasonal burn window; increased likelihood of crown fire; increased fire severity
Decreased amount (load)	Decreased fire intensity and seasonal burn window; decreased likelihood of crown fire; decreased fire severity
Increased horizontal continuity	Increased fire frequency and size, increased spatial homogeneity
Decreased horizontal continuity	Decreased fire frequency and size, decreased spatial homogeneity
Increased vertical continuity	Increased fire intensity and likelihood of crown fire, which could increase size and spatial homogeneity
Decreased vertical continuity	Decreased fire intensity and likelihood of crown fire, which could reduce size and homogeneity
Change in bulk density	Change in fire frequency, intensity, and seasonality; change in fire severity
Increased plant tissue flammability	Increased fire frequency, intensity, and seasonal burn window; possible increase in fire frequency or severity
Decreased plant tissue flammability	Decreased fire frequency, intensity, and seasonal burn-window; possible decrease in fire frequency or severity

[a] Modified from Brooks and others (2004) table 1.

duration of smoldering combustion, which influence fire severity. Intrinsic fuel properties such as plant tissue flammability, influenced by moisture content or chemical composition (for example, the presence of salts or volatile oils), also affect fire behavior.

Nonnative plants can alter fuelbeds directly, based on their own extrinsic and intrinsic properties as fuels, or indirectly by altering the abundance and arrangement of native plant fuels. If fuelbed characteristics are changed to the extent that fire type, frequency, intensity, severity, size, spatial complexity, or seasonality is altered, then the invasive plant has altered the fire regime. Plant invasions that alter fire regimes typically do so by altering more than one fuel or fire regime property (Brooks and others 2004). For example, grass invasions into shrublands increase horizontal fuel continuity and create a fuel bed bulk density more conducive to the ignition and spread of fire, thereby increasing fire frequency, size, and spatial homogeneity (in other words, completeness of burning). At the same time, the replacement of shrubs with grasses generally decreases the total fuel load, resulting in less heat release and decreased fire residence time and possibly reduced fire severity on the new, grass-dominated fuelbed. Reduced severity allows nonnative annual grasses to recover quickly following fire and establish fuel and fire regime conditions that could persist indefinitely.

The Invasive Plant Fire Regime Cycle

A conceptual model was recently developed describing the four general phases that lead to a shift in fuelbed composition from native to nonnative species, culminating in a self-sustaining invasive plant/fire regime cycle in which nonnatives dominate (Brooks and others 2004) (fig. 3-4). This process begins with *Phase 1*, before nonnative species disperse into and establish in the region of interest. Potential invader propagules are located in adjacent geographic areas or associated with potential vectors of spread (for example, contaminants of hay mulch or seeding mixes) and are poised to disperse into the region. The significance of this phase is that management can be focused solely on the prevention of propagule dispersal and the early detection and eradication of individuals or groups of individuals before populations can become established. *Phase 2* is characterized by the (1) establishment, (2) persistence, and (3) spread of a nonnative species (chapter 1). This requires that the species overcome local environmental and reproductive barriers, for example, the absence of an appropriate pollinator. Initial populations typically establish and persist in areas with substantial anthropogenic disturbances, such as urban, agricultural, or roadside sites. *Phase 3* is marked by the emergence of substantial negative ecosystem effects, or "ecological harm" as described in chapter 1; examples include reduction of native species abundance and diversity and deterioration of habitat for native animal species (Mack and D'Antonio 1998). In *Phase 4*, the negative effects of the nonnatives on native plants, and the presence of the nonnatives themselves, combine to alter fuel properties sufficiently to shift at least one characteristic of the subsequent fire regime outside of the reference range of variation. If the new fire regime favors the dominance of the invasive species causing the new fuel conditions and negatively affects the native species, an invasive plant/fire regime cycle becomes established (fig. 3-5).

The establishment of an invasive plant/fire regime cycle is of concern to land managers for two primary reasons. First, it may alter fuels and fire regimes in ways that impact human health, safety, or economic well-being. For example, invasions may increase "hazardous fuels," increasing the potential for fire-caused damage to human life, property, or economic commodities, particularly in wildland/urban interface areas. The second major concern for land managers, and the one most pertinent to management of

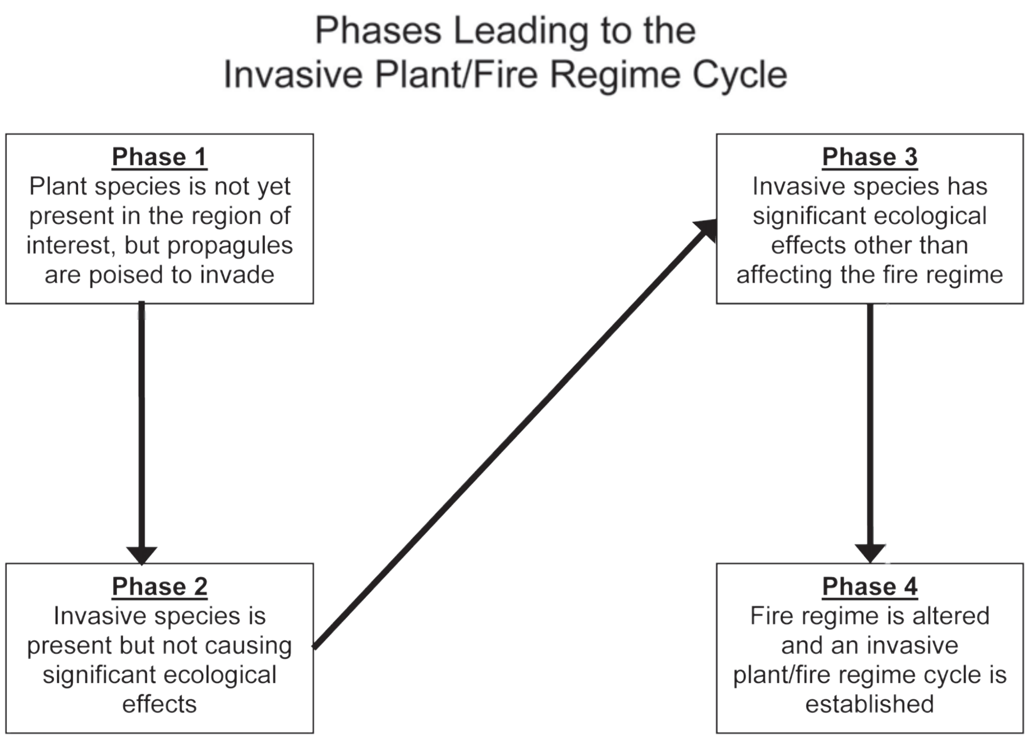

Figure 3-4—Phases leading to the establishment of an invasive plant/fire regime cycle,modified from Brooks and others (2004).

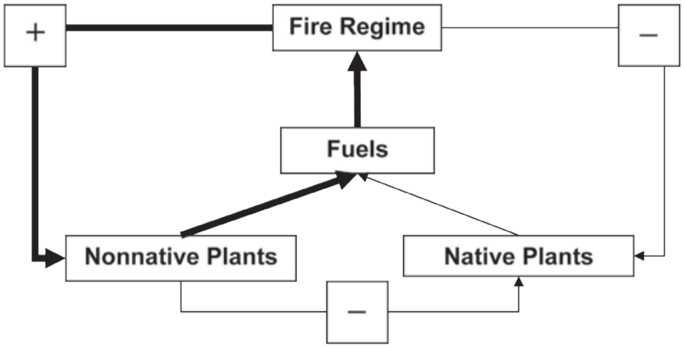

Figure 3-5—The invasive plant/fire regime cycle. Modified from Brooks and others (2004).

wildlands, is that altered fire regimes may have substantial negative effects on native plant and animal populations and ecosystems. The invasive plant/fire regime cycle may increase fuels or increase the rate of fuel replenishment after fire, leading to increased fire intensity or frequency; or it may reduce fuels in ways that suppress the spread of fire in ecosystems where fire is desirable. Disturbance regimes are strong forces driving the evolution of species, and the shifting of fire regime variables outside the range of variation to which they are adapted can tip the balance in plant communities toward new suites of dominant species. The resulting changes in vegetation may affect higher trophic levels. For example, cheatgrass (*Bromus tectorum*) and medusahead (*Taeniatherum caput-medusae*) now dominate 25 to 50 percent of sagebrush steppe in the Great Basin (West 2000), reducing habitat for the greater sage-grouse (*Centrocercus urophasianus*), a species experiencing declining population levels (Sands and others 2000). This change in vegetation has also reduced black-tailed jackrabbit (*Lepus californicus*) populations, which in turn has decreased the carrying capacity for golden eagles (*Aquila chrysaetos*) at the Snake River Birds of Prey National Conservation Area in Idaho. In the same area, Piute ground squirrel (*Spermophilus mollis idahoensis*) populations fluctuate more dramatically when sagebrush cover is lost, which may adversely affect prairie falcon (*Falco mexicanus*) populations (Sands and others 2000; Sullivan 2005). In the Mojave Desert, the replacement of native shrublands with nonnative annual grasslands dominated by red brome (*Bromus rubens*) reduces forage quality and habitat structure for the federally threatened desert tortoise (*Gopherus agassizii*) (Brooks and Esque 2002). When habitats are altered to the degree that existing wildlife populations cannot survive, new populations may invade or increase in dominance, and ecosystem properties may be further altered.

Predicting the Effects of Plant Invasions on Fire Regimes

Plant invasions that only affect the quantitative magnitude of pre-existing fuel properties (continuous-trait invaders, Chapin and others 1996) are likely to have less impact than those that alter the more fundamental qualitative properties of the existing fuelbed (discrete-trait invaders, Chapin and others 1996). For example, a nonnative grass that invades an existing grassland may quantitatively change the fuel load and/or the continuity of fuels somewhat, but it does not represent a qualitatively new fuel type. In contrast, a woody plant invading the same grassland represents a qualitatively different fuel type and is likely to have a much greater impact on fuel conditions and the reference fire regime. For example, in prairies in the Willamette Valley of Oregon and the Puget Lowlands of Washington the invasion of woody plants has shifted the fire regime from a frequent, low-severity regime fueled by grasses and herbaceous vegetation, to a mixed-severity regime with longer fire-return intervals and accumulations of woody fuels (chapter 10).

Although many publications and models relate fuel characteristics to fire behavior, relatively little has been documented relating plant invasions, fuelbeds, and fire behavior to fire regimes. To determine that an invasive plant/fire regime cycle has been established one must (1) document that a plant invasion or set of invasions has altered fuelbed characteristics, (2) demonstrate that these fuelbed changes alter the spatial and/or temporal distribution of fire on the landscape, and (3) show that the new regime promotes the dominance of the fuels that drive it (fig. 3-6). This requires evidence that spans multiple fire-return intervals. Evidence can accumulate rapidly if the change results in shortened return intervals. However, if the change results in longer fire-return intervals, many decades to centuries may need to elapse before there is enough evidence to show that an invasive plant/fire regime cycle has in fact established. Although it may be very difficult to obtain the information necessary to definitively document that an invasive plant/fire regime cycle has established, reasonable inferences can be made based on a comparison of fuel and fire behavior characteristics of the invading species (fig. 3-6, steps 1 and 2) and estimated reference conditions in the habitats they are invading.

An excellent example of how indirect inference can be used to evaluate the potential for an invasive plant/fire regime cycle is provided by Rossiter and others (2003). These authors tested two assumptions of D'Antonio and Vitousek's (1992) grass/fire model:

1. Nonnative grass invasions alter fuel loads and fuelbed flammability.

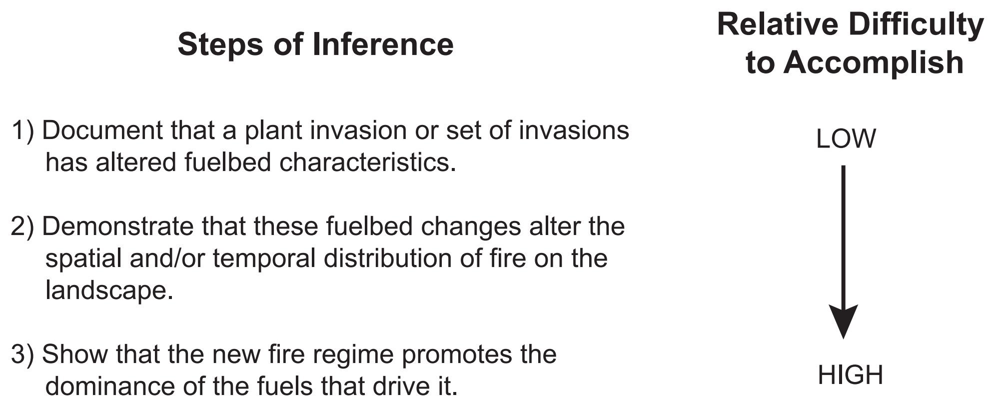

Figure 3-6—Steps required to determine the establishment of an invasive plant/fire regime cycle.

2. These changes increase fire frequency and/or intensity compared to uninvaded vegetation.

Their results indicate that a perennial grass invader from Africa, Gamba grass (*Andropogon gayanus*), can create fuelbeds with seven times more biomass than those created by native Australian savanna species. This higher fuel load led to a fire that was eight times more intense than other fires recorded in native fuelbeds during the same time of year, and produced the highest temperatures of any early dry season fire ever recorded in Northern Territory, Australia. Although this study did not demonstrate that the invading species preferentially benefited from the fire behavior it created, numerous examples from other ecosystems suggest that African grasses typically benefit from frequent, moderate to high intensity fires (Brooks and others 2004; D'Antonio and Vitousek 1992).

Another good example where indirect inference was used as evidence for an invasive plant/fire regime cycle comes from the Mojave Desert of western North America. Fires were historically infrequent and relatively small in this ecosystem that is dominated by sparse native desert vegetation (Brooks and Minnich 2006). Invasion by nonnative annual grasses from Eurasia has increased the amount, continuity, and persistence of fine fuels (Brooks 1999a; Brooks and Minnich 2006). The nonnative species that have caused these fuelbed changes include cheatgrass at higher elevations, red brome at middle elevations, and Mediterranean grass (*Schismus arabicus*, *S. barbatus*) at lower elevations (Brooks and Berry 2006). Fire often spreads exclusively in these fine nonnative fuels (Brooks 1999), allowing fires to occur under conditions where they otherwise would not. In addition, fires are larger following years of high rainfall that stimulate the growth of these nonnative annual grasses (Brooks and Matchett 2006), and these nonnnative species often dominate postfire landscapes within a few years after burning, setting the stage for recurrent fire (Brooks and Matchett 2003; Brooks and Minnich 2006). Some areas in the northeastern part of the Mojave Desert have recently experienced fires in excess of 100,000 ha (250,000 acres) (Brooks and Matchett 2006). Historical photographic and other anecdotal evidence suggest that since red brome invaded the region around 1900, fire-return intervals may have become as short as 20 years in some places, compared to historical estimates of greater than 100 years (Brooks and Minnich 2006). U.S. Bureau of Land Management photographs from the region clearly show continuous fuelbeds of red brome within a few years following fires that occurred during the 1940s. Thus, these invaders have altered fuelbeds, influenced fire behavior, recovered quickly following fire, and may have led to fire-return intervals on the order of 20 years in some places, all results that support the assumptions of both D'Antonio and Vitousek's (1992) grass/fire model and the invasive plant/fire regime cycle presented here. A similar example can be cited for cheatgrass in the Great Basin Desert of western North America (see discussion on page 40 and in chapter 8).

Herbaceous Plant Invasions

Herbaceous plants produce mostly fine fuels (1-hour timelag), which typically contain a high proportion of dead tissue late in the fire season. This is because the aboveground parts of herbaceous plants characteristically die back each year, either completely (for example, annuals, biennials, geophytes) or partially (for example, some perennial grasses, herbaceous shrubs).

Fine fuelbeds dominated by dead fuels respond rapidly to atmospheric conditions, especially with increased or decreased moisture content following changes in ambient relative humidity. Some herbaceous species create fuelbeds that do not readily carry fire because they have fuel moisture contents that are too high, horizontal continuities that are insufficient, or fuel bed bulk densities that are less than ideal for combustion. However, other species produce fuelbeds that can readily carry fire because they have low fuel moisture, high horizontal continuity, and fuel bed bulk densities that are conducive to combustion. Based on these parameters, forbs are generally the least flammable herbaceous invaders, and grasses (especially annual species) the most flammable.

Where highly flammable nonnative herbaceous plants have increased horizontal continuity of fine fuels, fires may be larger and more uniform than in uninvaded sites. Easy ignition and high fuel continuity, coupled with rapid recovery of nonnative herbs following fire, result in lengthy annual fire seasons and short fire-return intervals. Successive years of high rainfall and accumulation of dead herbaceous fuels can be associated with increased area burned (for example, Rogers and Vint 1987). The herbaceous fuels at the start of a given fire season consist mainly of litter from the past year's growth; later in the fire season, they are mostly comprised of the current year's growth (Jim Grace, personal communication 2006; M. Brooks personal observation, Mojave Desert uplands, spring and summer 1993). During drought periods, when herbaceous production is low, fuel load and continuity, and resulting probability of fire, tend to be low as well.

Perhaps the best known example of an invasive plant/fire regime cycle caused by an herbaceous plant is the invasion of the nonnative annual cheatgrass into sagebrush-steppe regions of the Intermountain West of North America (Brooks and Pyke 2001). Cheatgrass creates a type of fuel bed that was not previously present in this region (fig. 3-7). The altered fuel bed facilitates the ignition and spread of fire between adjacent shrubs (fig. 3-8). After fires occur, cheatgrass recovers rapidly, producing a fuel bed that can carry fire after as few as 5 years (Whisenant 1990a). Many native plants in this community, especially the subspecies of big sagebrush, are adapted to a longer fire-return interval and cannot persist where cheatgrass invasion substantially reduces the time between fires. Thus, cheatgrass both promotes frequent fire and recovers soon following fire, creating an invasive plant/fire regime cycle that has converted vast landscapes of native sagebrush-steppe to nonnative annual grasslands (chapter 8; Menakis and others 2003). These vegetation changes can cascade to higher trophic levels, affecting wildlife prey and predator species as well (reviewed by Brooks and others 2004).

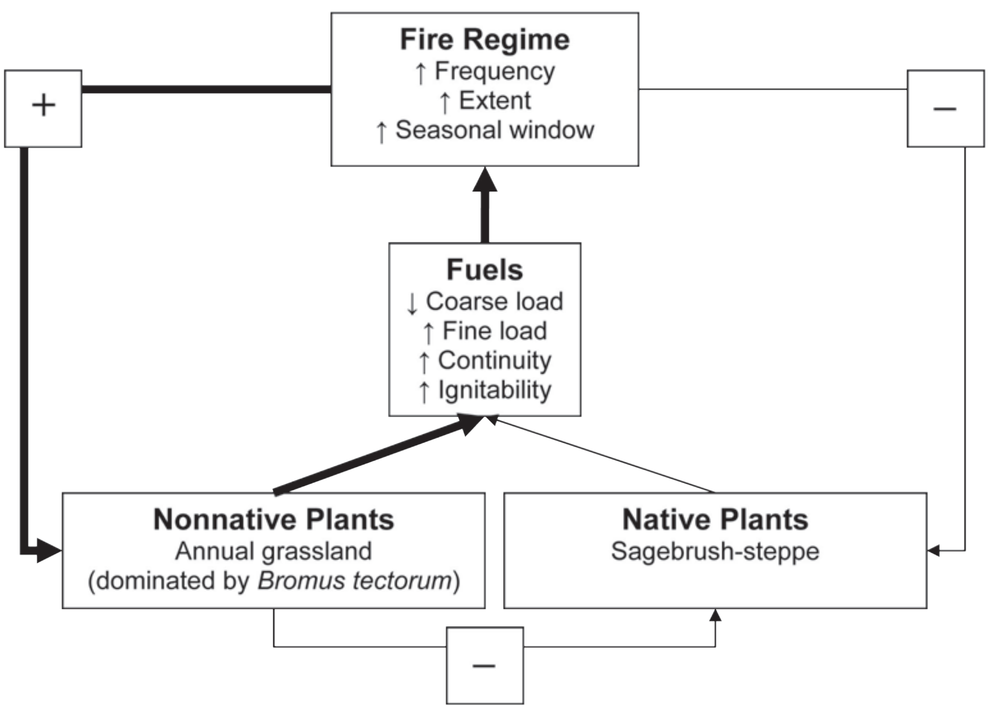

Figure 3-7—Changes in fuelbed and fire regime properties caused by the invasion of nonnative annual grasses into native sagebrush-steppe in the Intermountain West of North America.

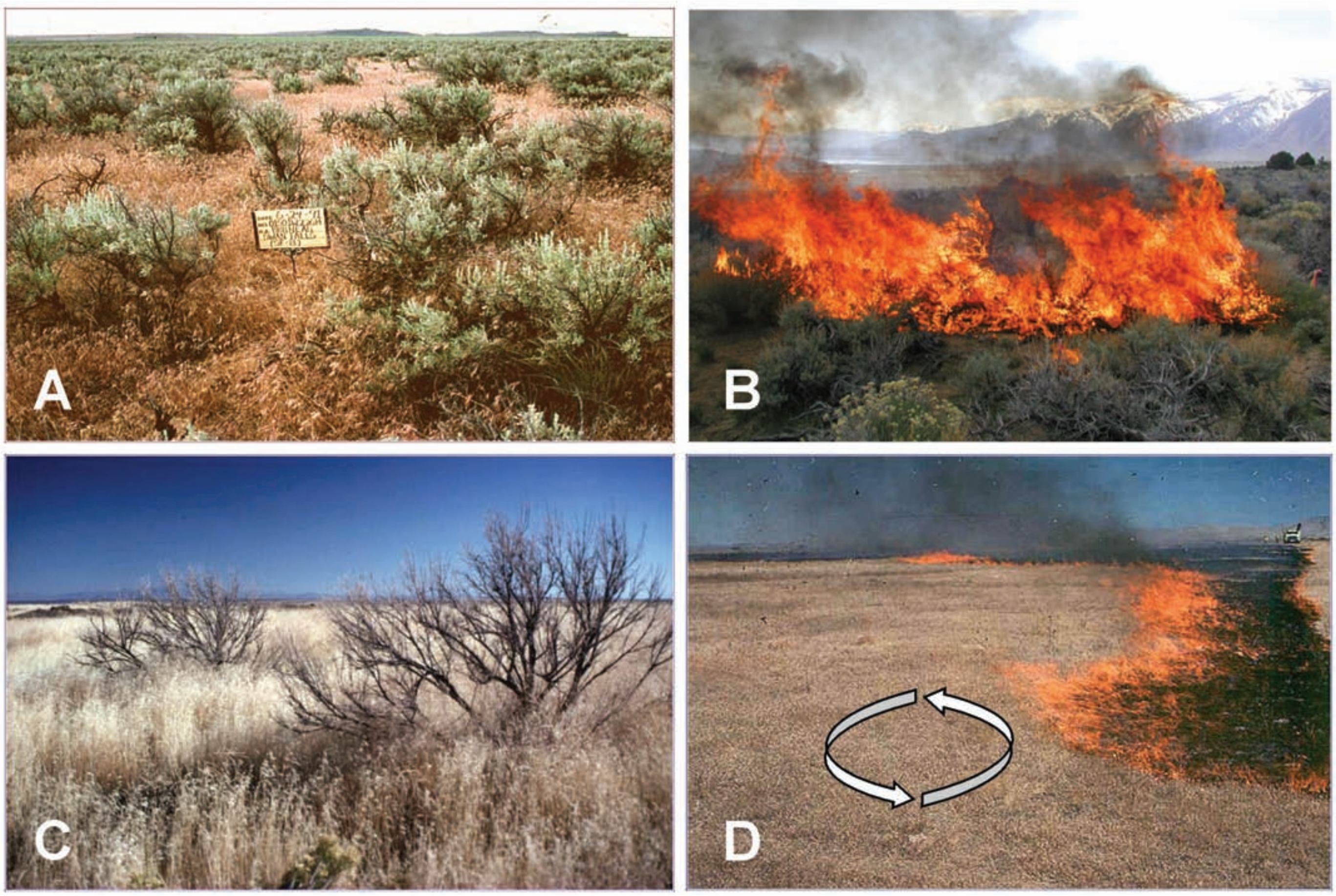

Figure 3-8—Cheatgrass leading to an invasive plant/fire regime cycle in the Intermountain West of North America. (A) Initial invasion filling interspaces between shrubs creating fuelbeds of fine and woody fuels; (B) initial fires; (C) subsequent fuelbed dominated by fine fuels with few woody fuels; (D) recurrent fire that perpetuates fine fuelbeds. (Photos A, C, and D by Mike Pellant, BLM; photo B by J. R. Matchett, USGS Western Ecological Research Center.)

The fuel changes caused by cheatgrass invasion include increased fine fuel loads, horizontal continuity, and ignitability of fuels (figs. 3-7 and 3-8). These fuelbed characteristics lead to increased fire frequency, size, and seasonal window of burning. As shrublands have been replaced by grasslands, coarse woody fuels have been replaced by fine grasses. This may lead to decreased fire residence times and possibly reduced fire intensities, although these changes have not been specifically documented.

Other examples of herbaceous plant invaders that may increase fire frequency include other annual grasses (for example, red brome) and perennial grasses (for example, buffelgrass (*Pennisetum ciliare*), fountain grass (*Pennisetum setaceum*), Johnson grass (*Sorghum halepense*)) in desert shrublands (chapter 8) and the Pacific Islands (chapter 11), Japanese stiltgrass (*Microstegium vimineum*) in northeastern forests (chapter 5), climbing ferns (*Lygodium* spp.) in the Southeast bioregion (chapter 6), and Japanese knotweed (*Polygonum cuspidatum*) in the Northwest Coastal bioregion (chapter 10). While empirical evidence for fire regime change is lacking in many of these examples, differences in fuel characteristics between invaded and uninvaded areas imply that there is potential for such changes.

There are cases when herbaceous perennial plants may decrease fire frequency and intensity, especially when the invaders have high live fuel moisture. The invasion of iceplant species (for example, *Carpobrotus* spp., *Mesembryanthemum* spp.) into coastal sage-scrub in California appears to have reduced the likelihood of fire in some areas (M. Brooks, personal observation, coastal southern California, Ventura County, summer 2000). Invasion of cactus species (for example, *Opuntia* spp.) into fire-adapted matorral shrubland in Spain may be having a similar effect, as fires have been noted to be less frequent and intense where cacti have invaded (Vilà and others 2005). This could have deleterious consequences for "fire followers," species that depend on the fire regeneration niche to complete their life cycles.

Herbaceous species that have allelopathic effects on other plants, such as diffuse knapweed (*Centaurea diffusa*) (Callaway and Aschehoug 2000; Callaway and Ridenour 2004), may reduce fine fuel loads and thereby reduce the frequency and size of fires. In some cases, plant invasions such as these may suppress extant nonnatives that previously altered the fire regime (for example, *Bromus* spp.), and dynamics between the two nonnatives, native plants, and the fire regime may settle into a new cycle.

Woody Plant Invasions

Woody shrubs and trees produce coarse fuels (10-hour timelag and larger) in addition to fine fuels from twigs and foliage. As woody plant canopies approach closure, herbaceous surface fuels may be suppressed. The coarser structure of woody fuelbeds compared to herbaceous fuelbeds can narrow seasonal burning windows and lengthen fire-return intervals, especially if this change is accompanied by reduction in fine surface fuels. Horizontal continuity of fuels is highly variable, leading to highly variable size and occurrence of unburned patches. Fuel loads can be relatively high and contain a high proportion of dead tissue, especially in old stands with deep accumulations of duff and litter. These conditions can lead to intense, stand-replacing fires and significant soil heating (thus increased fire severity). Examples include mesic shrublands and evergreen and deciduous forests.

The replacement of continuous, fine, grassland fuels by more patchy, coarse shrubland and woodland fuels (fig. 3-9) has reduced the frequency of fire in a number of places worldwide (Bruce and others 1997; Drewa and others 2001; Gordon 1998; Grace and others 2001; Miller and Tausch 2001; van Wilgen and Richardson 1985). Fire exclusion often facilitates the early stages of these invasions by extinguishing fires before they spread and/or reducing fine fuels through intensive livestock grazing. However, at some point the altered fuelbeds reduce the chance of fire due to their inherent characteristics. The longer fire is excluded and woody species persist with their patchy distribution, the greater the chance that topsoil and the underlying distribution of soil nutrients will shift from homogeneous patterns characteristic of grasslands to patchy patterns

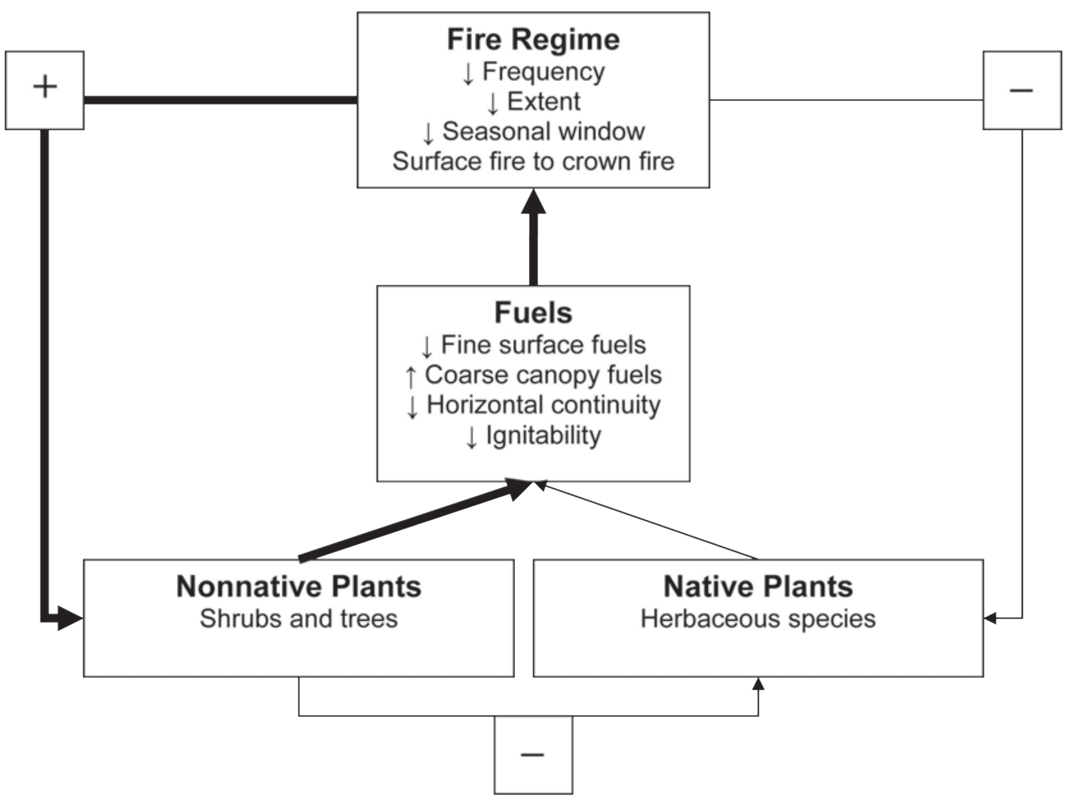

Figure 3-9—Changes in fuelbed and fire regime properties caused by the invasion of nonnative woody shrubs or trees into native herbaceous plant assemblages.

characteristic of shrub- and woodlands (Schlesinger and others 1990). Although positive feedback cycles between invading woody fuels and native grassland fuels have not been established over multiple fire-return intervals, it seems likely that these changes can be characterized as an invasive plant/fire regime cycle. This may be especially true if soil conditions, such as the spatial distribution of soil nutrients, change to the point where their patchiness does not support the continuous vegetation cover (Schlesinger and others 1996) needed to re-establish a reference regime of frequent, low-intensity fire.

Invasion of Chinese tallow (*Triadica sebifera*) into coastal prairie is a good example of how a tree invasion can alter fuels and fire regime properties (Bruce and others 1997; Grace and others 2001; chapter 7). As tallow trees invade, they overtop and shade out surface vegetation, resulting in reduced fine grass and forb surface fuels and increased coarse woody fuels (fig. 3-10). The fuelbed that results from Chinese tallow invasion is comprised mostly of canopy fuels, with few surface or ladder fuels. As a result, fires are difficult to start. If they do start, the high live fuel moisture content of Chinese tallow usually precludes spread into their crowns (Jim Grace, personal communication 2006). Although there are currently no data documenting a positive feedback loop between long fire-return intervals and dominance by Chinese tallow, the species' capacity for vigorous resprouting and rapid growth, and relatively low postfire mortality rates of mature trees, suggest that it can recover rapidly after fire and continue promoting a long fire-return interval. Theoretically, grasslands invaded by woody species that have reduced fine fuels and lengthened

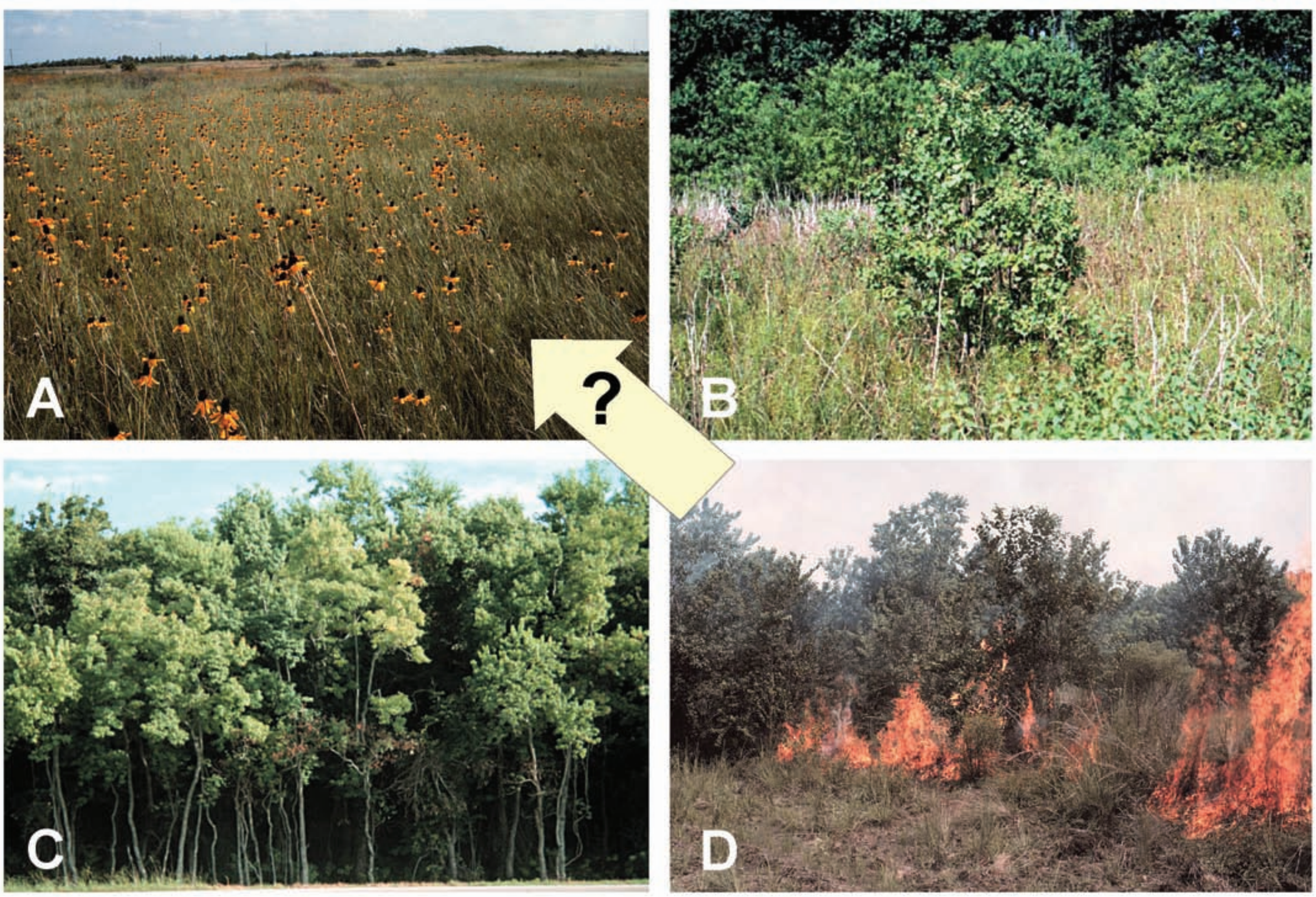

Figure 3-10—Chinese tallow creating a closed-canopy forest that drives out native surface fuels and may result in an invasive plant/fire regime cycle in the Gulf States of North America. (A) Uninvaded prairie of fine fuels. (B) Early invasion adding woody fuels. (C) Late invasion creating a fire resistant stand of closed-canopy woody fuels and few fine surface fuels. (D) To allow native prairie to recover, fire may be needed to control Chinese tallow at early stages of its invasion before closed-canopy stands become established. (Photos by Larry Allain, USGS, National Wetlands Research Center.)

fire-return intervals could support crown fire under very hazardous fire weather conditions. However, thus far no studies have described this phenomenon.

Saltcedar (*Tamarix ramosissima, T. chinensis*) provides an example of how a woody plant invader can alter fuel characteristics of native riparian assemblages comprised largely of woody species (chapter 8). Saltcedar produces a nearly continuous litter layer that is highly flammable (M. Brooks, personal observation, lower Colorado River, San Bernardino County, California, summer 2000). Fires that start in these surface fuels can easily carry through mature saltcedar trees and up into the canopies of native riparian trees. This may result in a frequent, high intensity, crown fire regime where an infrequent, low to moderate intensity, surface fire regime previously existed (Brooks and Minnich 2006). Saltcedar can resprout readily after burning and benefit from nutrients released by fire, whereas native woody riparian plants often do not resprout as vigorously (M. Brooks, personal observation, Virgin River, Clark County, Nevada, summer 2005; Ellis 2001). Although there are no quantitative descriptions relating saltcedar invasions to fire regime changes, numerous anecdotal observations and accounts suggest that this species can establish an invasive plant/fire regime cycle in riparian ecosystems in western North America (Dudley and Brooks 2006).

Preventing or Mitigating Altered Fire Regimes

Exclusion of potentially threatening species before they invade and early detection and rapid response to eradicate populations at the very early stages of invasion are the most cost-effective and successful approaches to preventing the establishment of an invasive plant/fire regime cycle. These approaches focus on *Phase 1* (dispersal) and *Phase 2* (establishment, persistence, spread) of the cycle (fig. 3-11). The cost of control is lowest and probability of successful management is highest during *Phase 1*. There may be economic costs associated with exclusion of plant species that are used in ornamental horticulture or as livestock forage, but these short-term costs would be eclipsed by the long-term costs of inaction if the species moves into phases 2 to 4. After a species has established multiple local populations during *Phase 2*, management costs begin to rise and the probability of successful prevention or mitigation of negative effects begins to decline, but management can still be focused entirely on the invasive plant species. In contrast, once *Phase 3* begins, management must focus on controlling the invader, revegetating native plant communities, and possibly also restoring ecosystem processes (other than fire regime) that have allowed invasion or have

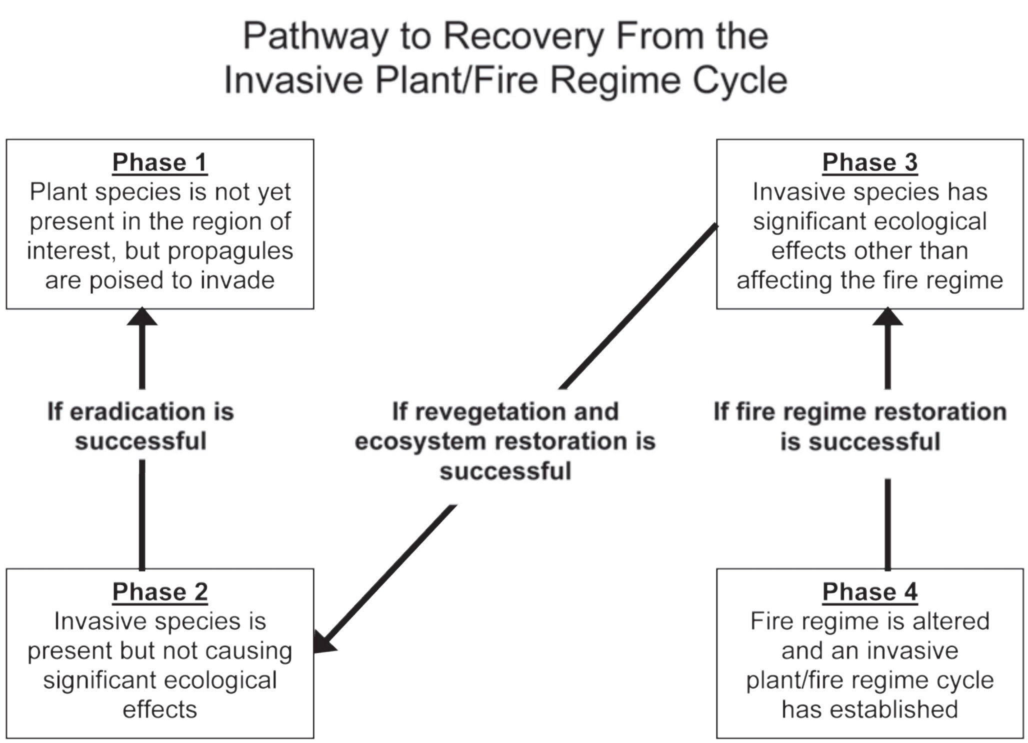

Figure 3-11—Steps toward breaking the invasive plant/fire regime cycle and reversing the effects of plant invasions on native plant communities and ecosystem properties, modified from Brooks and others (2004).

been altered by the invader. When *Phase 4* is reached and an invasive plant/fire regime cycle has been established, the invader needs to be controlled, native vegetation needs to be re-established, and various ecosystem processes, including the fire regime, must be restored. Thus, as each successive phase of the cycle is reached, additional management considerations are added, costs increase, and the probability of successful management decreases (Brooks and others 2004).

Summary Recommendations

Recommendations for management can be related to the steps of invasion and fire regime change shown in figure 3-11. Regarding *Phase 1,* plant species that have not yet invaded a region need to be evaluated for their potential to establish, become invasive, cause ecological impact, alter fuels, and eventually alter fire regimes. Species with high potential to alter fire regimes should be prioritized for exclusion from a region. Regarding *Phase 2, s*pecies that have persisted or begun to expand need to be evaluated for their potential to cause significant ecological impact and alter fuels. Species with a high potential to cause negative impact or alter fuels need to be prioritized for control. Regarding *Phase 3,* species that have already caused significant ecological impact need to be evaluated for their potential to alter fuels and fire regimes under any of the environmental conditions that occur in the region. Species with high potential to alter fire regimes should be prioritized for control, and restoration of pre-invasion plant community and ecosystem properties may be necessary. Species that introduce qualitatively novel fuel characteristics should in general be considered greater threats than those that only change fuel conditions quantitatively. Regarding *Phase 4,* when a species has already changed one or more fire regime characteristics, the altered regime needs to be evaluated for its potential to have negative effects on public safety, property, local economies, natural resources, and wildland ecosystems. Ecosystem effects may include reduced biodiversity of native species, loss of wildlife habitat, promotion of subsequent invasions by other nonnative species, altered watershed functioning, loss of tourist appeal, and increased fire-associated hazards.

In some cases, it may not be possible to restore communities to their pre-invasion state. For example, fire-enhancing tropical grasses from Central America and Africa have invaded seasonally dry habitats in the Hawaiian Islands, increased fire frequency, and reduced the amount of native forest. Restoration of pre-invasion native vegetation was found to be difficult, and managers have instead created “replacement communities” of native grassland species that are more fire tolerant than forest species and can coexist with the nonnative grasses (Tunison and others 2001; chapter 11).

Nonnative species that are not invasive may also be used in postfire revegetation to compete with invaders and recreate pre-invasion fuel characteristics to help restore altered fire regimes. For example, the nonnative bunchgrass crested wheatgrass (*Agropyron desertorum*) has been seeded into postfire landscapes in the Great Basin desert of North America to suppress growth of the nonnative annual cheatgrass and reduce fuel continuity and flammability (Hull and Stewart 1948). The idea is that nonnative bunchgrasses can help restore a pre-invasion fire regime of infrequent, low intensity fire, which will allow native plants to re-establish more easily. This process has been referred to as “assisted succession” (Cox and Anderson 2004). Proponents anticipated that, if the desired fire regime can be maintained, over time the original native plant species may be gradually reintroduced. It is difficult to say how successful this management approach has been because effectiveness of past postfire emergency stabilization, rehabilitation, and restoration in the United States has not been monitored (GAO 2003). However, current studies are in progress to provide some of this information.

In this chapter I have presented a number of examples of how plant invasions can alter fire regimes. Although the ecological implications of these changes can be significant, one must remember that few plant invasions will result in fire regimes shifted beyond their reference conditions. Even so, the potential effects of invaders on fire regimes must be considered along with other potential effects when prioritizing plant invaders for management (for example, Warner and others 2003). To help in this task, I have described key elements linking fuel conditions with fire regimes that can help in screening plant invaders for their potential effects. This task would further benefit from additional examples of cases where invasions by nonnative plants have altered fire regimes. There are very likely many examples that await discovery, especially in contexts where these relationships may not be expected or otherwise cause people to take notice.

Notes