FIRE AND ALIEN PLANTS IN HAWAI‘I: RESEARCH AND MANAGEMENT IMPLICATIONS FOR NATIVE ECOSYSTEMS

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ABSTRACT

Fire, an important evolutionary determinant in many continental ecosystems, probably has not played a significant role in the State. The most common natural ignition source is lava flows, but the majority of fires are now started by humans. Some native plant species, *e.g.,* koa (*Acacia koa*), ‘a‘ali‘i (*Dodonaea viscosa*), ‘ōhi‘a *(Metrosideros polymorpha)*, and ‘ūlei *(Osteomeles anthyllidifolia)*, show some tolerance of fire, which may be a legacy of their pre-insular biology. Most species, *e.g.,* pūkiawe *(Styphelia tameiameiae)*, are severely set back, killed, or compete poorly with alien vegetation stimulated by fire. The natural fire regime in Hawai‘i has been markedly altered by the rapid spread of alien grasses, particularly broomsedge (*Andropogon virginicus*), molasses grass (*Melinis minutiflora*), bush beardgrass (*Schizachyrium condensatum*), and fountain grass (*Pennisetum setaceum*). These alien grasses are stimulated by fire. As a result, fire frequencies and sizes have increased, resulting in the intensification of alien plants to the detriment of native species. Fire is now a very powerful disturbance factor in Hawaiian ecosystems, not as extensive as the depredations of feral animals but certainly as destructive. Fire frequency will probably continue to increase and affect natural areas more seriously because of the spread of alien grasses. Fire, therefore, cannot be used as a management tool in the restoration or preservation of native Hawaiian ecosystems. The protection of natural areas can be enhanced by aggressive fire suppression and presuppression planning, including construction of fuel breaks, preparation of fuels distribution maps, strengthening of interagency fire agreements, and fire prevention.

INTRODUCTION

Fire, in Europe and the U.S., was traditionally thought of as a negative factor in natural ecosystems (Pyne 1982). This philosophy was epitomized by the highly effective U.S. Forest Service "Smokey the Bear" advertising campaign. However, in the last 20 years, fire has been acknowledged to play a vital, natural role in many ecosystems. In fact, periodic low-intensity fires maintain certain forest types that would otherwise be highly altered by the occasional major conflagration (Kilgore 1981). Other ecosystems are subject to infrequent, high-intensity fires without long-term harm (Heinselman 1981).

The natural ecological role of fire is well understood in temperate areas, particularly North America, and in the subtropics, principally Australia. In wet tropical areas, there is little evidence that fire plays a role in the maintenance of natural ecosystems (Mueller-Dombois 1981). Fire, usually started by humans, degrades tropical forests. Pyrophytic grasses typically invade burned sites, and grass-dominated areas expand due to increasingly frequent and destructive subsequent fires. The vast majority of savannah ecosystems are fire-dependent and almost certainly man-induced, although herbivores also play a significant role in maintaining them (Buechner and Dawkins 1961). A few grasslands, however, are not fire-dependent (Sarmiento and Monasterio 1974). Fire has not been reported as an important natural factor in most island ecosystems. However, once humans colonize an island, fire is used aggressively as a vegetation management technique (Kirch 1982), and accidental fire frequency increases.

In this paper, we characterize changes in the natural fire regimes in Hawai'i and discuss the current ecological effects of fire in natural ecosystems. These observations serve as the basis for recommendations about fire management and research in natural areas throughout the State. The information and recommendations in this paper are based mostly on studies and experiences of researchers and fire managers working in Hawaii Volcanoes National Park, where fire history records are relatively complete, fire effects studies have been conducted, and active programs of fire suppression and fire prevention have been in place since the mid-1970s.

THE NATURAL FIRE REGIME IN HAWAI'I

The natural fire regime in Hawai'i is difficult to reconstruct in detail. Accounts of natural fires are rare and contain little ecological information. Lack of annual tree growth rings precludes developing a precise fire history based on fire scar chronologies. Radiocarbon dating of charcoal found in soil and bogs has the potential to indicate broad patterns of fire occurrence, but most carbon-dating studies have been conducted by geologists interested in dating lava flows or by anthropologists interested in cultural sites. Moreover, carbon in volcanic sites may indicate fires along the immediate edge of flows or phreatic eruptions, rather than free-burning fires. The published literature on carbon-dating of charcoal deposits in Hawaiian bogs is meager and not useful for detailed fire history studies. A serious study of buried carbon as an indicator of natural fire frequency is needed.

J. Juvik and P. Scowcroft (pers. comm.) have confirmed the probable occurrence of fire prior to human colonization. Juvik found carbon at depth in a core from an O'ahu bog revealing a 26,000-year record of fire occurrence. Scowcroft reported undated carbon burned at a depth of 0.5 m in Laupāhoehoe Forest Reserve on Hawai'i Island, a location that suggests the occurrence of wildfire rather than volcanic activity. J.P. Lockwood (pers. comm.) found evidence of natural fire in a widely distributed pattern of carbon dates on the northern, eastern, and southeastern slopes of Mauna Loa, all approximately 400 years old and not consistent with local flows. This pattern suggests the possibility of a large fire, possibly ignited by Keamoku lava flows of that age.

The paucity of carbon in subsurface soils formed before human colonization and away from volcanically active areas implies a low fire frequency. Carbon dating in Hawaii Volcanoes National Park, which should have the highest occurrence of soil carbon because of volcanic activity, confirms this pattern. Soil profiles from three Park sites, Kīpuka Ki, Kīpuka Puaulu (Mueller-Dombois and Lamoureux 1967), and 'Ōla'a (Mueller-Dombois 1981), indicate the absence of fires over the last 2,000 years, although charcoal is associated in these sites with phreatic eruptions (J.P. Lockwood, pers. comm.). However, these are mesic and wet sites, and soil pits in dry sites might indicate a different pattern.

A low natural frequency of fire is also implied by the infrequency of natural ignition sources, low flammability of native vegetation, and discontinuous distribution of natural fuels (Mueller-Dombois 1981). Vogl (1969) suggested that lightning was a more frequent source of fire than commonly believed. However, lightning-initiated fire is uncommon (Sorensen 1979; Mueller-Dombois 1981), although strikes without fire spread are responsible for tree mortality in rain forest (Sorenson 1979; J.T. Tunison and J. Leialoha, unpub. data), and lightning strikes are known to have started a few recent grassland fires (Kartinawata and Mueller-Dombois 1972; Tunison and Leialoha 1988). Fires started by lava flows are common during volcanic eruptions, at least in alien grass fuels. However, volcanism is highly localized in Hawai'i, being confined mostly to one island at any one point in time (Mueller-Dombois 1981).

Flammable, fire-dependent, or fire-maintained vegetation did not characterize most original, undisturbed Hawaiian vegetation types. The low flammability of native fuels implies poor adaptation to fire (Mutch 1970). Few native species have oils or resins frequently associated with fire-adapted plants, although *Dubautia* and *Dodonaea* may have. Moreover, most vegetation types were dominated by open stands of trees and shrubs (Mueller-Dombois 1981). Alpine and subalpine plant communities were characterized by a sparse to open cover of low shrubs with localized patches of grass. Before disturbance, the submontane seasonal vegetation zone was dominated by woodlands with an understory of open shrubs, sedges, lichens, and bryophytes. The rain forest vegetation zone is almost invariably wet, and litter usually recyles rapidly, although uluhe *(Dicranopteris linearis)*-dominated rain forest can carry fire after extended dry periods. Pre-Polynesian coastal vegetation is not well understood. Pili grass *(Heteropogon contortus)*, possibly indigenous to

Hawai'i, may have been abundant in some areas. Dryland forest, which may have been much more widespread, does not support fine fuels to carry fire.

The apparent fire tolerance of some native plants is less clearly indicative of past natural fire regimes than fire history, ignition sources, flammability, and fuel distribution. Some native species do not recover well from fire, but these species may eventually recover from seed and be important late in plant succession. The fact that other native plants can resprout after fire does not imply that they are specifically adapted to fire. Mueller-Dombois (1981) suggested that adaptations to various natural stress factors provides a good explanation for fire tolerance of some native species. In addition, ancestral populations of certain species may have been adapted to fire prior to their establishment in Hawai'i. The ability to resprout after fire is found in species characteristic of plant communities unlikely to carry fire. For example, many rain forest woody plants (*e.g.,* kāwa'u, *Ilex anomala*) and tree ferns (*e.g., Cibotium glaucum*) resprout vigorously after fire (J.T. Tunison, unpub. data). Yet, many lowland trees in Hawai'i, *e.g.,* lama (*Diospyros sandwicensis*) and wiliwili (*Erythrina sandwicensis*), which grow in relatively dry environments, do not resprout. Recovery of native plants from fire is also difficult to evaluate in Hawaiian ecosystems because it is strongly influenced by competition from alien vegetation. Native vegetation may recover adequately from fire, but it is often masked by the prolific spread of alien plants.

In conclusion, the natural fire regime in many areas of Hawai'i is best characterized as fire-independent (Vogl 1975). Pre-settlement fires were probably irregular, infrequent, short-term ecological perturbations from which vegetation eventually recovered; fires were thus insignificant as long-term evolutionary factors (Mueller-Dombois 1981).

FIRE REGIME SINCE THE ARRIVAL OF MAN

Polynesians colonized Hawai'i approximately 1,600 years ago. They used fire extensively to manipulate vegetation in the lowlands in a "slash-and-burn" form of agriculture, which created an anthropogenic landscape (Kirch 1982; Cuddihy and Stone 1990). The Polynesian landscape was characterized by open grasslands, and pioneer species predominated below 1,475 ft (450 m) in the Hilo area and below 1,970 ft (600 m) in the Ka'ū area (McEldowney 1979). Continuous burning through the years resulted in the formation of the open savannah observed by several early visitors (Kirch 1982). A. Menzies, for example, observed a fire burning in the coastal grasslands of Kaua'i in 1792, which the local inhabitants said was set to stimulate the growth of pili grass, used for thatching. Apparently since European contact, fire frequency and size have generally been low, although large fires have occurred occasionally (Hall 1904; Vogl 1969). The majority of fires are now started by people, either intentionally or inadvertently.

The fire regime in Hawai'i has changed dramatically in recent decades, with a considerable increase in fire frequency and probably fire size. An altered fire regime is reflected in the fire history of Hawaii Volcanoes

National Park, the only natural area with continuously recorded fire history over the last 60 years. Most of the fires (73%) in the Park have been caused by humans. Twenty-five percent were ignited by lava flows in an area with the highest incidence of volcanism in the State, and 2% were caused by lightning (National Park Service 1990).

Fire frequency and size increased greatly in Hawaii Volcanoes after 1968. Twenty-seven fires, averaging 10 a (4 ha), were recorded between 1920 and 1967. Since then, 58 fires have burned an average of 507 a (205 ha) each. The increase in fire frequency and size can be attributed to an accumulation of fine fuels, primarily alien grasses, which spread and intensified in the 1960s and 1970s. Photopoints and exclosure studies indicate that increase of grasses in the coastal lowlands coincided to the removal of feral goats (*Capra hircus*) in the early 1970s (Mueller-Dombois and Spatz 1975; Mueller-Dombois 1980). During this period, the proliferation of perennial grasses such as thatching grass (*Hyparrhenia rufa*), Natal redtop (*Rhynchelytrum repens*), pili grass, and molasses grass (*Melinis minutiflora*) produced a many-fold increase in biomass and a fuel bed capable of supporting fire. Broomsedge (*Andropogon virginicus*) and bush beardgrass (*Schizachyrium condensatum*) invaded and spread throughout the submontane seasonal zone during the 1960s and 1970s, in spite of the presence of feral goats. The first fire carried by these grasses was reported in 1968 (Smathers, pers. comm.). Increased volcanic activity and greater numbers of visitors may have also contributed to the increased number and average size of fires in Hawaii Volcanoes National Park (National Park Service 1990).

Wildland fires in Hawai'i have been mostly confined to mesic and dry habitats, although the largest historic fire in the State occurred in rain forest (Vogl 1969). As alien bunchgrasses invade wetter habitats, fires will burn more frequently in these areas (Mueller-Dombois 1973).

EFFECTS OF FIRE IN HAWAIIAN ECOSYSTEMS

As a modifier of natural vegetation, fire is equal in importance to, but not as widespread in natural communities as, feral ungulates and alien plants. Twenty-three of the 86 alien plants that Smith (1985) characterized as disruptive weeds in native Hawaiian ecosystems resprout after fire. Fourteen are stimulated by fire, and only eight are eliminated by fire. Native plants, adapted to a very low frequency of fire, recover to some degree after burns, but typically to populations far less than those found in pre-burn conditions because they typically must compete with fire-stimulated alien grasses. Fires establish a destructive cycle by increasing fuel loadings of flammable alien grasses, which in turn increase fire frequency and fire size. The current ecological role of fire in Hawai'i is consistent with other tropical areas, where fire, usually of anthropogenic origin, type-converts tropical forest to savannah or grassland. Pyrophytic grasses typically invade burned sites, thus rendering them more fire-prone. Subsequent burns further inhibit the reestablishment of tree species (Mueller-Dombois 1981).

Not much published fire effects information exists in Hawai'i, particularly for long-term successional patterns. However, a comprehensive study of fire effects in Hawaii Volcanoes National Park is under way, and some tentative conclusions about fire effects can be made from the limited literature available and unpublished data of the authors and other researchers:

1. Alien grasses usually recover to pre-burn levels and often intensify after fire. Fire facilitates the spread of broomsedge, bush beardgrass, molasses grass, and fountain grass. These are fire-adapted alien grasses from the tropics, subtropics, and warm-temperate areas and are the most important widespread alien fuels in Hawai'i. Smith *et al.* (1980) described increases in broomsedge (*Andropogon* spp.) and molasses grass after fire. Hughes (1989) found an increase in cover of alien grasses and a shift in dominance from *Andropogon* spp. to molasses grass. Fire thus promotes conditions that increase fire frequency and size by increasing the continuity and/or fuel loadings of alien grasses. Hughes (1989) also found that a second fire at the same site can further degrade native Hawaiian vegetation, intensifying alien grass and fuel loadings.

2. Woody alien plants usually invade burned areas only to a limited degree and are typically early successional species. Alien shrubs such as partridge pea (*Chamaecrista nictitans*), indigo (*Indigofera suffruticosa*), sourbush (*Pluchea symphytifolia*), and yellow Himalayan raspberry (*Rubus ellipticus*) invade burned sites immediately after fire but appear to be early successional species. Other common trees and shrubs, such as common guava (*Psidium guajava*), lantana (*Lantana camara*), koa haole (*Leucaena leucocephala*), faya tree (*Myrica faya*), and Java plum (*Syzygium cumini*), resprout vigorously. Koa haole also establishes by seed.

3. A number of native plant species are fire-tolerant, although no native plant is fire-resistant. In other words, aerial portions of all native plant species are readily killed by fire, but some resprout or recover from seed. Māmane (*Sophora chrysophylla*) resprouts from the base (Mueller-Dombois, 1981), but the cover of the tree is reduced significantly for at least five years. Seed viability is diminished by fire (C.W. Smith, unpub. data). Koa (*Acacia koa*), although killed by high-intensity fire, regenerates profusely from seed (Scowcroft and Wood 1976) and/or vegetatively by means of root suckers (Warshauer 1975). Wester and Wood (1977) found that weeds, particularly Koster's curse (*Clidemia hirta*), outgrew koa seedlings within two years after fire. T. Parman and C.W. Smith (unpub. data) noted an inverse relationship between the severity of canopy scorching and sucker growth. Mueller-Dombois (1981) concluded that koa will coexist with fire as long as the forest is reestablished before the next conflagration. Naio (*Myoporum sandwicense*) also resprouts after fire as long as the fire is not too intense. Regrowth is slow and the original canopy cover takes over five years to regenerate.

The seeds of 'a'ali'i (*Dodonaea viscosa*) germinate readily after fire, but it is not known if they are fire-stimulated (Hughes 1989). 'A'ali'i may reach higher densities after fire than before (Hughes 1989).

Sandalwood (*Santalum* spp.) appears to reach its highest densities in recently burned areas. It recovers well vegetatively (Warshauer 1974) and appears to become established from seed. Several species of ʻōhelo (*Vaccinium* spp.) also regenerate rapidly from epicormic and root sprouts (L.L. Loope and C.W. Smith, unpub. data). However, they take at least five years to reestablish their cover and stature.

Most native bunchgrasses recover rapidly after burning. Pili grass resprouts readily with a significant increase in cover following low-intensity fire (J.T. Tunison, unpub. data). The aboriginal Hawaiians used fire to stimulate fresh growth in pili (Kirch 1982). ʻEmoloa *(Eragrostis grandis)* (Smith *et al.* 1980) and the native tussock grass *Deschampsia nubigena* (L.L. Loope and C.W. Smith, unpub. data) also resprout after fire.

Three native ferns regenerate after burning. Bracken (*Pteridium aquilinum*) resprouts rapidly after fire, often appearing within 10 days. Its cover increases dramatically during the first three months but then declines rapidly to a level comparable with the pre-burn level. Hāpuʻu *(Cibotium glaucum)* and ʻamaʻu *(Sadleria cyatheoides)* are known to lose their fronds after fire, but most plants soon produce new leaves.

4. A number of widespread native plants are sensitive to fire and do not recover well from seeds or sprouts. Pūkiawe *(Styphelia tameiameiae)*, an important shrub in many communities in the submontane and montane seasonal zones, is readily killed by fire (Smith *et al.* 1980) and does not become established from seed (Hughes 1989). Uluhe fern is very fire-sensitive and recovers slowly, if at all. ʻĀkia *(Wikstroemia sandwicensis)* and lama in the coastal lowlands are also easily killed by fire.

5. The fire tolerance of ʻōhiʻa *(Metrosideros polymorpha)* varies with fire intensity. ʻŌhiʻa recovers by resprouting epicormically or more usually from the root crown; seedlings are rare. Few ʻōhiʻa recovered from high-intensity fire (Hughes 1989). Smith *et. al.* (1980) noted approximately 50% recovery, with higher recovery rates correlated with the number of boles in a coppice. J.T. Tunison (unpub. data) observed 70% recovery in a low-intensity burn and less than 10% recovery in a high-intensity burn.

In Hawaiʻi, fire effects and fire potential vary among ecosystems. Fire appears to be more deleterious to native ecosystems below 4,600 ft (1,400 m) elevation than above. Fire potential is greatest in environments subject to seasonal drought, especially those invaded by alien grasses and previously affected by fire.

Subalpine Ecosystems

In subalpine ecosystems, fires are rare natural events, but a few fires of human origin have occurred. The māmane/naio forest tolerates fire to a certain extent (P. Scowcroft, pers. comm.), but recovery of the native species is slow, and alien bunchgrasses rapidly invade the opened environment.

'Ōhelo-pūkiawe scrub does not tolerate fire (L.L. Loope and C.W. Smith, unpub. data). Pūkiawe is killed and is slow to become reestablished. When fire intensity is low, 'ōhelo shoots resprout, but recovery after high-intensity fire is only from root suckers. The native tussock grass *Deschampsia nubigena* recovers slowly but may achieve higher cover after fire (D. Mueller-Dombois and J.T. Tunison, unpub. data). 'Ama'u fronds are killed, but new ones are produced rapidly. A few other species, *e.g.*, kūkaenēnē *(Coprosma ernodioides)* and strawberry (*Fragaria chiloensis*), recover within a year or so after fire. However, all native species subsequently have lower cover values following fire, as compared with alien species, particularly velvet grass (*Holcus lanatus*) and sweet vernalgrass (*Anthoxanthum odoratum*). The fire potential of subalpine ecosystems is increasing because alien grasses, particularly sweet vernalgrass and velvet grass, are invading the naturally discontinuous fuel bed.

Montane Seasonal Ecosystems

The montane parkland ecosystem, a mosaic of koa stands, shrublands, and grasslands, demonstrates considerable adaptation to fire (Mueller-Dombois 1981), with rapid recovery of native plant species. Koa is sensitive to fire but regenerates very rapidly (Scowcroft and Wood 1976) and, with 'emoloa and bracken, produces abundant regrowth within a month. The rapid regeneration of koa from suckers often reaches beyond the original aerial boundary of parent trees. The native *Deschampsia nubigena* and mountain pili *(Panicum tenuifolium)* recover vegetatively. 'A'ali'i is one of the first native shrubs to reinvade burned areas, whereas pūkiawe recovers much more slowly. In montane seasonal communities elsewhere, fire has contributed to the spread of alien grasses, as demonstrated by the invasion of fountain grass in the Pōhakuloa area of Hawai'i Island.

Fire potential is relatively high in the montane seasonal zone because of the continuous arrangement of grasses and abundance of shrubs. The invasion of alien grasses such as fountain grass, *Andropogon, Schizachyrium,* and *Paspalum* spp. is increasing the fire potential in this ecological zone.

Montane Rain Forest Ecosystems

Documented fires in montane rain forest ecosystems are rare (Sorensen 1979; Mueller-Dombois 1981), and fire-effects studies in this zone have been limited to uluhe-dominated rain forest (J.T. Tunison, unpub. data). After fire, 'ōhi'a, kāwa'u, and other native trees typically resprout from the root crown. Hāpu'u and 'ama'u also recover vegetatively. However, the other common rain forest fern, uluhe, is eliminated from early successional stages, and alien species such as broomsedge and yellow Himalayan raspberry invade burned sites and become dominant. Fire potential is relatively low in rain forest because fuels rarely dry out and organic matter is rapidly recyled.

Submontane Seasonal Ecosystems

Many of the ecosystems in this zone have been disturbed significantly by fire. The lower elevations of this zone were occupied by the indigenous Hawaiians, who probably burned the area inadvertently or deliberately to clear land for agriculture, thereby selecting for fire-tolerant species. In the 1800s, many lowland areas were abandoned as the native Hawaiian populations were decimated by disease and the survivors moved. Fuel loadings were low in these principally native sclerophyllous woodlands because of the paucity of grasses. However, invasions of alien bunchgrasses have greatly increased fire frequency and size. Fire suppresses most native shrubs, particulary pūkiawe, ‘ulei (*Osteomeles anthyllidifolia*), and ‘ākia, and increases alien grass cover, particularly bush beardgrass and molasses grass (Smith *et al.* 1980; Hughes 1989). ‘A‘ali‘i is an early colonizer and may reach higher densities than in pre-fire communities. The fire potential of the submontane seasonal zone is now very high because of alien grasses.

Dry Lowland Ecosystems

This zone was the most heavily impacted by aboriginal Hawaiians, and alien plant species now dominate many coastal lowland areas. Many native species, for example, wiliwili and lama, remaining in this environment are not adapted to fire. For this reason, relictual native woodlands are now threatened by fine fuel loading from alien grasses.

Kartawinata and Mueller-Dombois (1972) observed that fire in the coastal lowlands of O‘ahu maintained and extended alien grass communities. Broomsedge, bush beardgrass, fountain grass, and thatching grass, as well as the native pili grass, have replaced shrub communities in Hawaii Volcanoes National Park after fire (J.T. Tunison, unpub. data).

There are extensive remnants of a forest dominted by hala *(Pandanus odoratissimus)*, ‘ōhi‘a, and uluhe inland of Kolo Point, Hawai‘i. These forest remnants have been burned on several occasions recently. Hala and the alien shrub Malabar melastome *(Melastoma candidum)* disappeared from the community very rapidly, and the aerial portions of ‘ōhi‘a have been killed. Alien broomsedge, bamboo orchid *(Arundina graminifolia)*, melochia (*Melochia umbellata*), and native hi‘aloa *(Waltheria americana)* commonly invade after each fire, whereas the native uluhe only reinvades as long as the forbs and shrubs are not too dense.

Koa haole and kiawe *(Prosopis pallida)* communities are frequently burned. The recovery rate of kiawe is approximately 20%. Fountain grass and buffel grass (*Cenchrus ciliaris*) rapidly invade or take over the area. Fire intensifies the cover of koa haole, which resprouts from the base and becomes established from seed. The fire potential of the coastal lowlands is very high because of low rainfall and continuously arranged fine fuels.

Coastal Strand Ecosystems

Coastal strand environments are rarely subjected to fire because most of the communities have insufficient fuel to carry it. The heavy salt loading from ocean spray may also retard fires. However, when these communities are burned the majority of the species are killed. The succulent species, such as naupaka kahakai (*Scaevola sericea*), are particularly sensitive. Other species, such as *Chamaesyce degeneri, Myoporum,* and

Wikstroemia, resprout. Coastal strand ecosystems are not readily invaded by alien grasses.

CONCLUSIONS AND RECOMMENDATIONS

The use of natural fire is not appropriate to the management of native ecosystems in Hawai'i. Studies and observations to date indicate that fires of all intensities, timing, and causes are harmful to most native ecosystems in Hawai'i. Alien species, particularly grasses, recover rapidly and fill in the spaces left by native plants, which recover more slowly, if at all. The intensification of fire-prone alien grasses following fire assures the increased incidence of fire, thereby establishing a self-perpetuating alien grass/fire cycle. The effects of fire argue strongly that all agencies responsible for the management of fire in natural areas in Hawai'i should aggressively suppress all fires, whether caused by lava flows, lightning, or humans. Fire size should be minimized, even though limited suppression resources may necessitate confinement or containment strategies, with control lines established at a distance from the fire, rather than direct attack.

Prescribed burning is not, on the whole, an effective management tool in Hawai'i, although it may have potential limited management and research value. On the U.S. Mainland, prescribed burning is useful in restoring natural ecological processes, rectifying anthropogenically altered vegetation patterns, reducing hazardous fuel loadings, enhancing wildlife habitat, and in a few cases controlling alien plants. However, fire is not useful in controlling alien plant species in native Hawaiian ecosystems, although it may be useful in controlling selected alien plants in managed systems dominated by alien plants. Kiawe and melastomes, for example, are relatively sensitive to fire and may be controlled by burning.

Prescribed fire in Hawai'i may be useful in accelerating the recovery of 'a'ali'i shrublands and koa forest or woodlands, because these two species are stimulated by fire. However, before fire is used for this purpose, the effects of fire on stimulating alien species, damaging sensitive native plants in these communities, and natural recovery should be considered. Fire may have been a natural ecological factor in montane seasonal shrublands, grasslands, and koa forest.

Prescribed fire may also be useful in managing habitat for the Hawaiian goose or nēnē *(Nesochen sandwicensis)*. Wildfire at Hawaii Volcanoes National Park provided an attractive, albeit short-term, food source in the form of resprouting bush beardgrass, broomsedge, and other alien grasses. Wildfire also created an open habitat favorable for nesting. There were twelve nesting attempts in 1987-1988 in the Uila Burn, an area with less than 17 attempts in the six years previous to the burn (H. Hoshide, pers. comm.). Fledgling success was apparently limited by mongoose (*Herpestes auropunctatus*) predation, which is controllable by diphacinone bait stations (H. Hoshide, pers. comm.).

Prescribed fire is essential in developing customized fuel models, which enable fire suppression personnel to predict fire behavior (rate of spread, fire intensity, fire size). This information is invaluable in developing fire suppression strategies. Prescribed fire is also important in understanding fire effects because pre-fire conditions can be characterized.

Suppression capabilities for wildland fire in natural areas are limited in Hawai'i by poorly developed detection, fire suppression, and logistical limitations in the State. Historically low fire frequency has resulted in complacency on the part of natural area managers; however, nowadays fires may become quite large and destructive. Some of these limitations can be overcome by following these measures:

1. Develop an aggressive program of fire prevention. Most fires are human-caused in Hawai'i. Alien grass fuels are spreading in the State at the same time that residential development is expanding into rural areas, and both trends increase the threat of fire to natural areas. A fire prevention program in Hawai'i should be developed around local symbols and themes to appeal to school-age children. A fire prevention consciousness among younger people can be raised by educational contacts from fire personnel in the schools, media messages, and fire prevention signing in fire-prone areas.

2. Formulate strong interagency agreements that provide rapid movement of fire fighters and resources to wildfires on one island or jurisdiction to another. This is especially important in Hawai'i, where limitation of personnel and equipment necessitate sharing resources, and islands with the most extensive natural areas have the smallest populations. Interagency agreements will develop a mobile, well-equipped, trained cadre of fire fighters from the Hawaii Department of Land and Natural Resources, National Park Service, Department of Defense, The Nature Conservancy, and counties. A unified fire organization can be developed by use of the Incident Command System, which is practiced widely on the U.S. Mainland and provides for common organizational roles, terminology, standards, and training. Interagency agreements can be reinforced by common training sessions sponsored by different agencies and a statewide coordinating committee that meets annually to discuss mutual problems and share information. The national system of fire danger rating should be used throughout Hawai'i.

3. Expand the scope of county fire departments to wildland fire. This measure will increase the cadre of fire suppression personnel and protect natural areas under county fire jurisdiction.

4. Allocate more funding to wildland fire to maintain high standards of preparedness, training, and effectiveness. More fire management specialist positions, unencumbered by collateral duties, should be established.

5. Establish fuel breaks in the most fire-prone areas to break up extensive fuel beds or protect particularly valuable biological resources. Hazardous fuels should be routinely reduced in areas of probable human-caused ignitions.

6. Develop a program of presuppression planning, rather than simply responding to fires once they occur. Presuppression planning includes all those actions taken to minimize fire size and improve suppression capabilities prior to a fire. In addition to establishing fuel breaks, it includes mapping the distribution of fuel types, fuel breaks, special biological resources, water sources, and helicopter landing sites. These maps serve as the basis for developing suppression strategies and tactics prior to fires.

The most important fire research needs in Hawai'i are an understanding of fire effects and the development of local fuel models. Fire effects studies have been conducted principally in Hawaii Volcanoes National Park and Pu'uwa'awa'a Ranch and should be undertaken in other natural areas in Hawai'i to indicate the response of fire in the variety of vegetation types present in the State. Studies at Hawaii Volcanoes have begun to determine why alien grasses are more successful than native plants after fire. The effects of fire exclusion on Hawaiian vegetation that evolved with fire, such as the montane seasonal type in Hawaii Volcanoes, should be investigated. In Mainland ecosystems, the exclusion of fire may result in destructive accumulations of fuel and the loss of species and community diversity.

Research should be conducted to establish fuel models for the State. Fuel models will allow rapid prediction of rates of spread, fire intensity, and size, the most important information in planning suppression or presuppression strategies. Preliminary work on characterizing Hawaiian fuels was undertaken by the U.S. Forest Service in the early 1970s (Fujioka 1976; Fujioka and Fujii 1980). These investigations and preliminary studies at Hawaii Volcanoes indicate that the standard Fire Behavior Models do not describe fuels beds dominated by broomsedge, bush beardgrass, and molasses grass. Fire behavior data from local fuels are insufficient to determine if the standard models accurately describe local fire behavior. If not, customized models can be constructed and revised based on fuel bed characteristics and, more importantly, actual fire behavior observed. A series of small prescribed fires is needed to provide a range of wind speed and fuel moisture conditions and measurement of fire and fuels under controlled conditions. The utility of customized fuel models needs to be closely considered before prescribed fire is used. The most important considerations include whether training of local fire managers is sufficient to use the modern fire behavior prediction system, how valuable fuel models are in grass fuels that have generally very high rates of spread from head fires and similar rates of spread on backing fire, impacts on native vegetation, low frequency of fire in Hawai'i, and costs to managers to conduct prescribed fire.

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