

forest threats

Socioecological Impacts of Multiple Forest Insect Outbreaks in the Pinaleno Spruce–Fir Forest, Arizona

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Multiple high-severity insect outbreaks and wildfires dramatically altered the character of the Pinaleno high-elevation forests with notable impacts on ecosystem services. The Pinalenos are a small mountain range positioned close to large population centers, but not so close that any large industry is dependent on their resources, so regional and local impacts of the insect outbreaks to provisional resources were minor. There were qualitative impacts to cultural services, particularly to recreation, but no documented economic impacts. Effects on carbon and fuels were significant, but affected firefighting operations more than wildfire severity. The Pinalenos are positioned in an area of high biodiversity, and impacts on habitats of unique species were sometimes positive but also sometimes severely negative, especially on a relict population of Engelmann spruce and the critically endangered Mount Graham red squirrel. The Pinaleno situation illustrates how ecological disturbances can have a minor immediate economic impact but severe impacts on ecosystems and ecosystem services.

Keywords: *Dendroctonus rufipennis*, *Dryocoetes confusus*, ecosystem goods and services, *Elatobium abietinum*, Engelmann spruce, Mount Graham red squirrel, *Nepytia janetae*

Multiple high-severity insect outbreaks and wildfires during the late 1990s and early 2000s dramatically altered the character of the spruce–fir forest in the Pinaleno Mountains of southern Arizona with notable impacts to ecosystem services. As is the case with many forest insect outbreaks, ecological effects were significant, some ecosystem goods and services were negatively affected, and a few were positively affected, but for the most part impacts were poorly quantified or documented. Characterizing and quantifying impacts to nonextractive goods and services

is a significant challenge to resource managers. The [Millennium Ecosystem Assessment \(2005\)](#) and The Ecosystem and Biodiversity synthesis ([Sukhdev et al. 2010](#)) provide a framework for evaluating impacts to ecosystem goods and services. Here I discuss the timeline of these events in the Pinaleno Mountains, effects on spruce–fir forest character, and subsequent impacts on ecosystem goods and services using that framework.

The Pinaleno Mountains in southern Arizona are a cool moist sky island in an otherwise hot, dry, desert environment. Sky islands are mountain ranges of sufficient

height to feature dramatically different environments between lowlands and uplands, and sufficiently isolated from other ranges to have developed unique ecologies. The Madrean Sky Island Archipelago encompasses about 40 island mountains between the Southern Rocky Mountains and the Sierra Madre Occidental, surrounded by Sonoran and Chihuahuan Desert grasslands and desert scrub ([Warshall 1995](#)). The archipelago represents an area of exceptional biodiversity with a mixture of Nearctic and Neotropical species, influenced by the Great Basin, Sonoran, Chihuahuan, and Great Plains biogeographic provinces ([Brown 1994](#)). The Pinalenos are the highest of these ranges, reaching 3270 m, encompassing the greatest cross-section of ecological communities found in the Southwestern US and supporting the highest diversity of habitats in the shortest vertical distance on any mountain range in North America ([Warshall 1995](#)). The elevational gradient found within a few kilometers in the Pinalenos is comparable with hundreds of kilometers in latitude. Pinaleno biotic communities are stacked vertically with increasing elevation, with Sonoran desert scrub or semi-desert grassland transitioning to Madrean

Received April 7, 2018; accepted July 10, 2018; published online October 13, 2018.

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Acknowledgments: Thanks to C.D. O'Connor for quantifying the unburned spruce–fir area and to the many authors whose papers I could not cite because of space limitations. Suggestions by three reviewers, the guest editor, J.L. Koprowski, C.D. O'Connor, and C.P. Wilcox helped improve the quality of the manuscript. This paper was funded in part by a grant from the Western Wildland Environmental Threats Center, USDA Forest Service, and was developed as part of a project of the Western Bark Beetle Research Group.

evergreen oak woodland, in turn to pine-oak woodland, to pine forest, and then to montane mixed-conifer, with spruce-fir at the highest elevations above 3050 m.

The Pinaleno spruce-fir vegetation community is the southernmost spruce-fir forest in North America; the Pinalenos and nearby Chiricahua Mountains are the southern range limit for Engelmann spruce (*Picea engelmannii*); and the Pinalenos and Santa Catalina Mountains are the southern range limit for corkbark fir (*Abies lasiocarpa* var. *arizonica*). The Pinalenos reach a higher elevation and have a greater land area suitable for mixed-conifer and spruce-fir forests compared with other Arizonan ranges in the Madrean Sky Island Archipelago. Although it comprises less than 1 percent of the Pinaleno forests, the 1220-ha spruce-fir forest is disproportionately important because of its unique characteristics and lack of representation elsewhere (Istock and Hoffmann 1995; USFS 2018). It is especially valued as a critical habitat for the critically endangered Mount Graham red squirrel (*Tamiasciurus fremonti grahamensis*, MGRS). Management issues related to establishment of the Mount Graham International Observatory (MGIO) made management of the Pinaleno spruce-fir forest one of the most contentious forest management issues in western North America for decades (Istock and Hoffmann 1995, Sanderson and Koprowski 2009). The Pinaleno high-elevation forests support a diverse range of ecosystem goods and services, providing high levels of biodiversity and endemism, habitat for several threatened and endangered species, recreation opportunities, spiritual enrichment encounters, astrophysical observatory sites, and other goods and services (USFS 2018).

Timeline of Events

Disturbance regimes in Southwestern spruce-fir forests are characterized by infrequent high-severity canopy-replacing fire and recurring bark beetle outbreaks of varying intensity, but include infrequent high-severity outbreaks (Vankat 2013, O'Connor et al. 2014, 2015). Bark beetles are the primary natural disturbance agents during multicentury, possibly millennial-length, fire-free periods (O'Connor et al. 2015). Spruce beetle (*Dendroctonus rufipennis*, SB) outbreaks became increasingly extensive, severe, and of longer duration

during the 20th century, due in part to increased abundance and extent of spruce in the adjacent mixed-conifer forest types during the fire-exclusion period (O'Connor et al. 2015). Recently, the Pinaleno high-elevation forests were uncharacteristically devastated by multiple concurrent and consecutive high-severity insect outbreaks followed by two canopy-replacing fires. Janet's looper (*Nepytia janetae*) completely defoliated about 65 percent of the Pinaleno spruce-fir area in 1996–99 (CNF 2014; Figure 1a). This geometrid is previously considered to be an obscure, innocuous species with no record of significant damage anywhere, and causal factors regarding this outbreak are unknown. Defoliated Engelmann spruce (*Picea engelmannii*) and corkbark fir were rapidly colonized by SB and western balsam bark beetle (*Dryocoetes confusus*, WBBB), respectively, initiating outbreaks of both bark beetle species (Wilson et al. 1999). The bark beetle outbreaks were markedly aggressive, killing the majority of defoliated spruce and fir of suitable size, and subsequently expanding to encompass the entirety of the high-elevation forest (CNF 2014). Near the end of the Janet's looper outbreak, spruce aphid (*Elatobium abietinum*, SPA), an exotic sap-sucking folivore, established in the Pinalenos. Single-season severe SPA events can kill 24–41 percent of Engelmann spruce within four years, and the initial outbreak in the Pinalenos was the most severe yet recorded in the Southwest (Lynch 2004, 2009). The SB outbreak may have been prolonged by SPA, as aphid-weakened spruce were subsequently attacked by SB (Lynch 2009) while the WBBB outbreak subsided in the corkbark fir.

Fire is infrequent in the Pinaleno spruce-fir but burns with high intensity and severe

effects when it does occur (O'Connor et al. 2014). Historically, a high-frequency low-severity fire regime in the downslope mixed-conifer maintained relatively open stands with low woody fuel accumulations, grassy understories, and elevated tree canopy layers. Fires spread extensively in the mixed-conifer and did not spread as crown fires into the shady, cool and moist conditions of the spruce-fir forest (USFS 2009, O'Connor et al. 2014). Fire exclusion in mixed-conifer forests from 1880 to the mid-1990s promoted excessive recruitment of shade-tolerant species, resulting in dense multistoried stands, excessive fuel accumulation, and conversion to a high-severity fire regime (O'Connor et al. 2014). Grissino-Mayer et al. (1995) predicted that under such conditions canopy fire in the mixed-conifer would spread to the upslope spruce-fir, which is what happened in the 2004 Nuttall Complex fire, leaving about 300 ha of relatively small trees mixed with fallen and standing insect-killed timber, and again in the 2017 Frye Fire, leaving only 14 ha of spruce-fir forest.

Forest Structure and Character

The cumulative effects of the insect outbreaks dramatically altered the character of the spruce-fir forest. Mortality approached 85 percent, converting the forest from a stable, mature condition to an early-successional state comprising small trees and standing dead timber (Lynch 2009, CNF 2014). SB and WBBB favored large trees, and SPA affected Engelmann spruce of all sizes. A major structural consequence was re-distribution of fuels, with fine foliar fuels and live canopy bulk density converted to surface fuels, and large standing timber converted to standing snags and coarse woody debris (Figure 1b). Snag fall during storm

Management and Policy Implications

Forest insect outbreaks have increased in size and intensity in recent decades and will have long-lasting legacies. Insect damage is usually quantified and described in terms of area affected, percent tree mortality, and altered species composition. Impacts on nonextractive goods and services can be difficult to assess. Mortality from multiple high-severity insect outbreaks in the Pinaleno Mountains spruce-fir forest killed about 85 percent of trees, yet fuelwood and timber impacts were nonexistent because products cannot be economically extracted from this specific area. The greatest impacts were on biodiversity and genetic resources, endangered species habitat, and wildland firefighting strategies. The Pinaleno situation illustrates how ecological disturbances can have a minor immediate economic impact but severe impacts on ecosystems and ecosystem services. Given the likelihood that large high-severity outbreaks and wildfires are likely to continue for the foreseeable future, the impacts describe here underscore the need to restore health and resiliency to western North American forests.

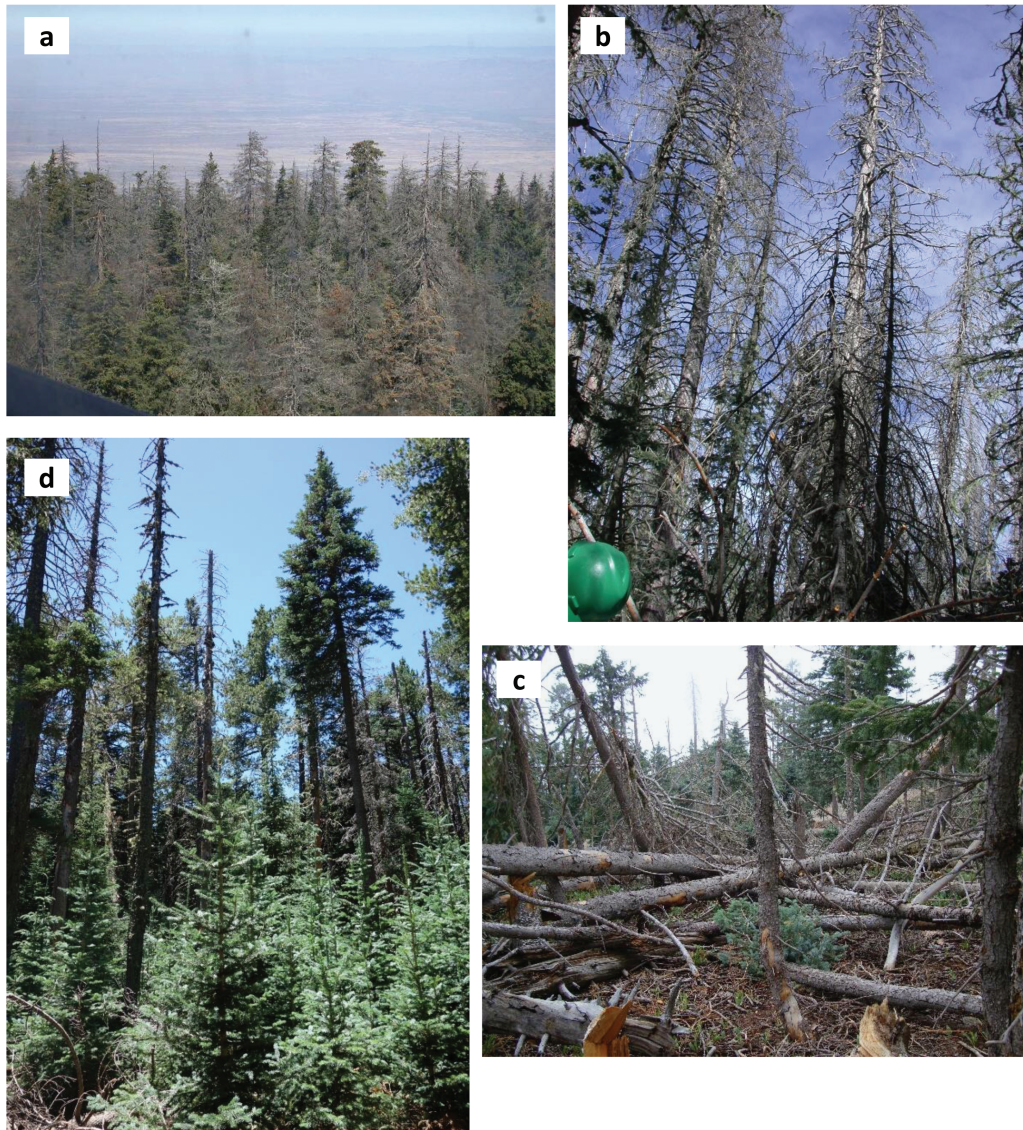


Figure 1. Photographs of the Pinaleno spruce–fir (a) in 2003 after the Janet’s looper outbreak and in the early stages of the bark beetle outbreaks, (b) after needle fall in 2005 or 2006, (c) in jackstraw in 2010, and (d) in 2016 as the forest recovers. All photos were taken by the author from or within 250 m of the Mount Graham International Observatory.

and wind events created jackstraw conditions (Figure 1c). Though small, some survivors were reproductive, and others rapidly increased in height and reached reproductive size. Postoutbreak recruitment was good, but favored corkbark fir over Engelmann spruce because of continued effects of SPA. This regrowth accumulated live shrub and canopy fuels intermixed with the jackstraw timber (Figure 1d). The insect outbreaks were the largest and most severe in the Pinalenos in both recorded history and a 319-year dendrochronologically reconstructed period (O’Connor et al. 2015).

Impacts to Provisional Services

Though close to large population centers (Phoenix and Tucson), the Pinalenos are a

small mountain range and not so close to those cities that any large industry is dependent on their resources.

Fiber

The outbreaks had little impact on fuelwood and commercial timber resources. It is not feasible to harvest timber from the Pinaleno spruce–fir forest today because of difficult access, lack of local infrastructure, and distance to milling facilities, but primarily because the spruce–fir forest is encompassed in a wildlife refugium where most access and commercial uses are legally prohibited.

Water Quality and Production

The effects of insect outbreaks on aquatic habitat, water production, and snowmelt

dynamics are not documented, and in any case would be minor in comparison with substantial watershed damage caused by the nearly 12,000 ha 2004 Nuttall Fire and 20,000 ha 2017 Frye Fire (Schaffner and Reed 2005).

Astrophysical Site

The insect outbreaks and subsequent clearing of trees surrounding the observatories probably improved the seeing conditions (generally, the blurring and twinkling of astronomical objects because of air turbulence) at MGIO. The three MGIO astronomical observatories occupy about 3.5 ha within the spruce–fir forest and were constructed with minimal forest clearing to preserve MGRS habitat (Istock and

Hoffmann 1995). Trees negatively affect astronomical seeing conditions by trapping a cold air layer near the ground surface and increasing turbulence above the canopy. Except for the observations noting that these undesirable conditions were present at MGIO (Taylor et al. 2004), improved conditions after the outbreaks and wildfires are not noted in the literature. Loss of the overstory significantly reduced canopy height by about 5 m where trees survived and in some places to near ground level (all of the photos in Figure 1 were taken from or within 250 m of MGIO), but these effects are likely to be temporary because of rapid regrowth of the forest.

Cultural Services

Native American Values

The Pinaleno range has high importance in Native American spiritual beliefs and cultural practices (Spoerl 2009, USFS 2009), but impacts on their values are difficult to document. Native American peoples from several Tribes cherish the mountain range (including integral ecosystems) as sacred and as home to mountain spirits, and they use indigenous plants and resources from all elevations for spiritual, ceremonial, and medicinal purposes. The Pinalenos have been formally recognized as a Traditional Cultural Property eligible for inclusion in the National Register of Historic Places, important to the Western Apache. Impacts on specific indigenous plants and resources are not documented in the available literature. Ceremonial cairns and shrines would presumably be more visible and subject to vandalism with reduced forest canopy cover, but rapid regrowth of the canopy (Figure 1d) would remedy this effect. Also, recreational access is prohibited in the MGRS refugium, minimizing the likelihood of visitors finding these places. To some extent, the outbreaks were considered a natural response of mountain spirits to past activities and development in the Pinalenos, especially the construction of MGIO. However, Tribes generally support Forest Service efforts to mitigate outbreak effects and to restore ecosystem resiliency (USFS 2009).

Recreation and Scenic Resources

The Pinaleno Mountains are accessible from large metropolitan areas and are therefore used for recreation, especially camping and hiking, spiritual encounters, appreciation of scenic beauty, and summer cabin residential

use. Fundamental to many visitors' experiences are the mountain range's natural beauty and temperatures, with summer temperatures 10–20°C cooler than in the nearby desert towns and cities. Most visitor destinations in the Pinalenos are to the pine and mixed-conifer forests, where outbreak impacts were mediated by the abundance of nonhost tree species. The public can visit the spruce–fir forest only through a permitted public education tour operation, which primarily offers tours of the observatories and lunch at a rustic visitor's center. People participating in these tours can see the effects of the insect outbreaks, but the observatories are the main attraction. Visitor numbers were not affected by the insect outbreaks, as weather and seasonal closures are the primary factors affecting tour numbers. The insect damage had little effect on the likelihood of return visits, and effects on visitor-generated revenues are not known but probably negligible. Local residents were more concerned about the impacts on MGRS habitat than on recreation opportunities (King 2003).

Regulating Services

Carbon

The total above ground biomass was 398 ± 262 Mg/ha in 2008, and approximately 157 ± 214 Mg/ha died during the outbreaks, as computed using numbers from Swetnam et al. (2016). Effects on sequestration and net primary productivity have not been determined.

Fuels and Fire Danger

Prior to the 2010s, it was commonly thought that insect outbreaks increased both wildfire likelihood and the severity of wildfire effects, but recent work has shown that insect outbreaks usually reduce, or have little effect on the wildfire likelihood, and generally reduce burn severity, though many issues remain unresolved (Meigs et al. 2015, 2016). Fire behavior is a function of fuels, weather, and energy or heat needed to initiate the exothermic reaction. Fine canopy fuels carry crown fires (Fuller 1991), and these fuels are the first to be affected by both defoliator and bark beetle outbreaks. In western North America, potential for active crown fire behavior sometimes increases briefly following bark beetle activity when red needles are still in the canopy, but rapidly and dramatically declines once needles fall (Simard et al. 2011, Hicke

et al. 2012, Jenkins et al. 2012, Donato et al. 2013, Meigs et al. 2015, 2016). The red needle stage in Pinaleno high-elevation forests is particularly short, as high winds in winter and spring, snowfall effects, and mid- to late-summer monsoon storms cause needles to fall rapidly regardless of the time of year and attacking insect species. Subsequent potential for surface-to-crown fire transition can remain low for decades because of reduced canopy fuels (Simard et al. 2011, Hicke et al. 2012, Jenkins et al. 2012, Donato et al. 2013), though burn residence time may increase because of coarse woody debris (Donato et al. 2013). Effects vary with temporal and spatial scales. This information on bark beetle outbreak effects on fire behavior was developed from scientific studies undertaken in response to modern changes in fire and insect outbreak regimes, generally becoming available after the Pinaleno insect outbreaks and the 2004 Nuttall Fire. The perception of high hazard, particularly by observatory personnel who had observed the 1996 Clark Peak fire burn to the edge of the spruce–fir, increased to alarming levels as tree mortality intensified and the outbreaks expanded (Flatten 2003 and numerous other media outlets). The initial looper outbreak surrounded the astrophysical site, and observatory personnel observed outbreak progression over 3 years, the transition to bark beetle outbreaks, continued decline of residual spruce that were damaged by SPA, and the expansion of these outbreaks beyond the horizon viewable from the observatories. By 2004, the overwhelming majority of the trees viewed from the observatories were dead, needles and small branchwood had fallen (but epiphytic lichens had not), and fire hazard was perceived to be extreme when it was actually lower than before the outbreaks.

Bark beetle-related tree mortality can significantly affect fire line construction time, snag mitigation operations, total heat output, residence burn times, and other factors affecting firefighter safety and firefighting operations (Jenkins et al. 2012). The extreme amounts of tree mortality surrounding the observatories, especially concentrated in large standing snags and jackstraw blowdown (Figure 1c), affected firefighting efforts to protect the observatories during both fires. Repeated burnout operations between the observatories and the advancing fire front resulted in high-severity burn effects in the 2004 Nuttall Fire.

Insect-killed trees in the unburned area were removed from the immediate vicinity of the observatories after the Nuttall Fire.

Surviving trees grew rapidly and would have served as progenitors of the future forest, but remained adjacent to and upslope of the overgrown mixed-conifer forest. By 2017, this rapidly increasing canopy (increasing in height and canopy bulk density, [Figure 1d](#)) was intermixed with snags, jackstraw blowdown, and coarse woody debris from the outbreaks, so firefighter safety conditions were arguably worse in 2017 than in 2004, and canopy fire again spread from the mixed-conifer forest to the recovering residual spruce–fir forest in the 2017 Frye Fire. Overall, the effects of the insect outbreaks on fuels and fire danger were initially perceived as bad when in fact fire hazard was reduced, but significantly affected firefighting operations.

Habitat and Supporting Services

Endangered and Sensitive Species Habitat

The insect outbreaks and wildfires impacted large areas of endangered species habitat, especially that of the critically endangered MGRS. Initially, there were short-term positive effects on MGRS and its habitat. A late-1990s MGRS population spike ([Koprowski et al. 2005](#)) is temporally associated with the looper outbreak, and it is likely that squirrel survival and reproduction increased because of feeding on fat- and nutrient-rich larvae in winter, though no studies were underway at the time to confirm this (Janet's looper larvae feed on Engelmann spruce and corkbark fir foliage in autumn through spring). MGRS feeds on SPA when aphid populations are high by licking aphids from the foliage, though this has no significant effect on the aphid population. Aphids and their honeydew are high in sugars and would provide an energy source for squirrels. Red squirrels are known to feed on bark beetles, but this is not confirmed for MGRS.

Ultimately the effects of the insect outbreaks and wildfires on MGRS habitat were catastrophic ([Koprowski et al. 2005](#), [Wood et al. 2006](#), [AZGFD 2017](#)). General habitat requirements include mature forest with sufficient cone-bearing trees to provide a two-year winter food supply; closed canopy to provide interlocking branches for arboreal travel (especially escape from

predators); logs (especially hollow logs) for surface travel; cool temperatures, moisture, and shade to provide microsite conditions suitable for cone caches and mushroom growth; and suitable snags or tree cavities for nests. Outbreak-related overstory mortality negatively affected almost all the required habitat characteristics ([Koprowski et al. 2005](#)). Engelmann spruce cones are a critical food resource, and impacts will persist until spruce mature to large size. The MGRS extinction risk increased because of the cumulative habitat destruction from the insect outbreaks and wildfires.

Effects of the outbreaks on Mexican spotted owl (*Strix occidentalis lucida*) and its habitat are not well documented, but were not severe, as the spruce–fir is secondary habitat, and the Pinalenos represent a small portion of the species distribution.

The Pinaleno high-elevation ecosystems provide habitat for several sensitive species ([USFS 2005](#)) that the outbreaks probably improved, though populations are not monitored. Several species occupy high-elevation meadows and stream-side areas that woody species encroached on during the period of fire exclusion. Habitat was expected to improve or increase for these species with proposed thinning and re-introduction of natural fire regimes ([USFS 2005](#)), so outbreak-related tree mortality would presumably have similar effects. These species include the white-bellied vole (*Microtus longicaudus leucophaeus*), its flea (*Catallagia duffneri*), and the Cimarron tiger beetle (*Cicindela purpurea cimarrona*). The Pinaleno monkey grasshopper (*Eumorsea pinaleno*) habitat may have been affected, but this species is known only from collection specimens taken in the Pinaleno spruce–fir and has been considered possibly extinct since before the outbreaks and fires.

Wildlife Habitat

Insect outbreaks can significantly affect bird and small mammal populations by directly altering food availability and by indirectly altering habitat suitability ([Martin et al. 2006](#)), but specific information is lacking. Wildlife biologists were concerned that insect outbreak- and fire-induced changes to vegetation were increasing predation on MGRS by migrating hawks using the sky islands as a migration corridor between the southern Rockies and the Sierra Madre Occidental, as the archipelago is oriented north–south between the southern Rockies and the Sierra

Madre Occidental. However, outbreak-related changes to hawk habitat and prey availability have been inconsequential compared with the proliferation of a nonnative tree squirrel (Abert's squirrel, *Sciurus aberti*). The Abert's squirrel population provides an abundant year-round food resource for avian predators, subsidizing larger populations of resident avian predators and subsequently increasing predation risk for MGRS ([McHugh 2017](#), [Goldstein et al. 2018](#)).

Woodpecker (Picidae) populations increase during bark beetle outbreaks, but not as much as might be expected ([Fayt et al. 2005](#), [Wegensteiner et al. 2015](#)). Bark beetles represent a seasonal resource because woodpeckers generally prefer the larger bark beetle instars. Factors influencing woodpecker fecundity, territoriality, and delayed predator-prey responses regulate woodpecker population density, mediating responses to increased food abundance ([Fayt et al. 2005](#), [Wegensteiner et al. 2005](#)). The dramatic changes in forest structure caused by high-severity disturbances can negatively affect the stability of woodpecker and other bird populations ([Martin et al. 2006](#)). Local managers surveyed the spruce–fir forest during the bark beetle outbreaks, searching for downy woodpeckers (*Picoides pubescens*) without success. Further information on avian and small mammal habitat responses to the Pinaleno outbreaks is lacking.

Biodiversity

Positioning of the Madrean Sky Island Archipelago at the convergence of four biogeographic provinces (Great Basin, Sonoran, Chihuahuan, and Great Plains; [Brown 1994](#)) and considerable topographic complexity contribute to high levels of biodiversity. The conservation value of peripheral populations is high because of isolation, genetic variation, and unique adaptations. These populations are important sources of genetic variation and can provide important insights into factors limiting species distribution and vulnerability to changing environmental conditions. Multiple disturbances such as those incurred recently in the Pinaleno Mountains threaten isolated populations with extirpation.

The insect outbreaks and wildfires greatly diminished the Pinaleno Engelmann spruce populations, and repeated SPA outbreaks and a warming climate threaten its persistence ([Lynch 2004, 2009](#), [CNF 2014](#)). Southwestern populations of Engelmann

spruce represent unique genetic resources (Rehfeldt 1994, Haselhorst and Buerkle 2013). They are adapted to spring drought, occasional winters without snowpack, warmer summer and winter temperatures, and lower relative humidity than elsewhere, traits that could prove valuable as the climate warms. The Pinaleno and Chiricahua populations are genetically pure *P. engelmannii*, while more northern populations show past introgression with *P. glauca* (Haselhorst and Buerkle 2013). The spruce gall adelgid [*Adelges cooleyi* (Hemiptera: Adelgidae)] found on Engelmann spruce in southeastern Arizona is also genetically distinct from all other populations (Ahern et al. 2009) and faces the same threats as its host.

Pocket gopher populations increase in areas affected by wildfire and bark beetle outbreaks (Capp 1976) and by understory vegetation changes associated with open stand conditions (Kalies et al. 2012), so although it was not confirmed in the Pinalenos, it is likely that the insect outbreaks increased the area or quality of pocket gopher habitat, especially where tree mortality approached 100 percent. Pocket gophers are generally considered pests, but they display a great degree of chromosomal variability and have a large diverse range (Patton 1972). The Pinaleno pocket gopher (*Thomomys bottae grahamensis*) is a high-elevation meadow inhabitant found exclusively in the Pinalenos, where a relatively large landmass of connected suitable high-elevation habitat contributed to development of clinal variation. Habitats in nearby mountain ranges are abruptly disjunct at different elevations, and clinal variation is absent. Comparing the Pinaleno population with those populations provides opportunities to study the effects of ecological isolation on chromosomal evolution (Patton 1972).

Regulating Services

Postfire Recovery of Plant Communities

Ironically, though establishment of the MGIO complex was controversial and opposed by several groups on the basis of perceived threats to MGRS habitat and Native American cultural values (Istock and Hoffmann 1995, Spoerl 2009), aggressive firefighting efforts aimed at protecting the observatories in the 2004 Nuttall Fire also protected the forest in the immediate vicinity. Though heavily damaged by the insect outbreaks, the ca. 300 ha fire-protected area

surrounding the observatories would have provided a substantially larger and more centrally located seed source than would have been present without the aggressive firefighting effort aimed at protecting the observatories (colonization of the spruce–fir forest after the 1685 high-severity fire took 185 years; O'Connor et al. 2015). This 300 ha area would have facilitated more rapid re-colonization of the 2004 burned area and more rapid development of suitable MGRS habitat than if firefighting efforts had not protected the observatories. Unfortunately, efforts to reduce stand densities and restore a natural fire regime in the downslope mixed-conifer forest, thereby reducing the risk of crown fire spreading from the mixed-conifer to the spruce–fir, were barely underway before the 2017 Frye Fire, and luck had run out—crown fire again spread from the mixed-conifer to the spruce–fir, and only about 14 ha of the spruce–fir forest survived.

Conclusions

The cumulative ecological effects of four consecutive and overlapping high-severity insect outbreaks in the Pinaleno spruce–fir forest are among the most severe reported for any western North America forest. Effects on extractive provisional resources such as fiber were minor, as the forest is not managed for timber production. Impacts on wildfire fuels and risk were perceived to be critically bad but were mostly positive, and negative fire-related impacts of note were to firefighting operations and firefighter safety. Impacts on supporting services were severe, especially on biodiversity and habitats of endangered species. Combined with the effects of two high-severity wildfires, these outbreaks put the persistence of a unique population of Engelmann spruce in jeopardy, and place the critically endangered MGRS at the brink of extinction. Habitats of other species, and various other supporting and cultural resources, were affected, but specific impacts have not been documented. The Pinaleno situation illustrates how ecological disturbances can have a very minor immediate economic impact but severely impact ecosystems and supporting services.

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