

THE ROLE OF FIRE IN THE ESTABLISHMENT AND SPREAD OF NONNATIVE PLANTS IN ARIZONA PONDEROSA PINE FORESTS: A REVIEW

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ABSTRACT

Arizona ponderosa pine (*Pinus ponderosa*) forests have undergone dramatic changes since the late nineteenth century. Management practices such as fire exclusion have resulted in increased surface and tree crown fuel loads. Consequently, large and severe wildfires have been occurring more frequently in the ponderosa pine forests of Arizona. Furthermore, prescribed fire, both with and without tree thinning, is being applied to ponderosa pine forests to mitigate the risk of wildfire. Increasingly, nonnative plant species are spreading into burned forests regardless of fire type. In this article, we review recent literature on nonnative establishment in the post-fire plant community. Current research suggests an increasing risk of nonnative establishment is associated with increasing fire severity. Furthermore, wildfires seem more likely to promote nonnative species establishment than prescribed fires. The results are inconsistent, however, with some high-severity fires having few nonnatives and some prescribed fires strongly promoting invasion. Further research is needed to understand the mechanisms of invasion. In the 23 studies we examined, a total of 43 nonnative plant species were reported in post-fire communities. Of these, only three species were listed as noxious in Arizona: field bindweed (*Convolvulus arvensis*), Dalmatian toadflax (*Linaria dalmatica*), and Scotch cottonthistle (*Onopordum acanthium*). Cheatgrass (*Bromus tectorum*), Kentucky bluegrass (*Poa pratensis*), and common mullein (*Verbascum thapsus*) were the most commonly observed species in burned areas, regardless of natural or anthropogenic ignition. Generally, nonnative presence increased after fire, but abundance of these species remained low (<10% cover). Changes in nonnative populations reported in Arizona are consistent with those seen in ponderosa pine forests of other regions, with nonnatives tending to increase with increasing fire severity.

INTRODUCTION

Fire plays an integral role in Arizona ponderosa pine (*Pinus ponderosa*) forests by regulating and maintaining tree density, understory species abundance and composition, litter accumulation, and many ecosystem processes (Weaver 1951, Cooper 1960, Hart et al. 2005, Laughlin and Fulé 2008). Starting in the late 1800s, ponderosa pine forests in Arizona were heavily grazed by livestock, reducing the fuels that carried surface fires through the system. In the early twentieth century, active fire suppression further reduced the acreage burned each year (Cooper 1960, Covington and Moore 1994). As a result, the forests have become densely stocked with ponderosa pines and depauperate of understory species. As in many western states, the increased density of trees, coupled with changes in climate, has led to a commensurate increase in the number of hectares annually burned by wildfire (Swetnam 1990, Covington et al. 1997, Westerling et al. 2006). In addition, more land is treated each year for fuels management and ecological restoration with prescribed fire (Interagency Fire Center; www.NIFC.gov), often in combination with mechanical tree thinning prior to burning. Wildland fire use (allowing naturally caused fire to burn for resource benefit) is also becoming a more widespread management practice. Disturbances created by these fires may facilitate the spread of undesir-

able nonnative plant species (hereafter nonnatives) into the burned landscapes (D'Antonio and Vitousek 1992, Keeley 2006). Regardless of whether the fire is prescribed or wild, nonnatives are frequently documented in the post-fire understory community of these forests.

Many nonnatives are well adapted to fire (D'Antonio and Vitousek 1992, Brooks et al. 2004). They are generally early successional species that can capitalize on open niches created by fire faster than their native counterparts (Rejmanek 1995). The impact of nonnatives in the post-fire community is highly variable. Some species, such as prickly lettuce (*Lactuca serriola*) and common dandelion (*Taraxacum officinale*), tend to have a subordinate role in the disturbed ecosystem. Conversely, other, more aggressive invaders, such as cheatgrass (*Bromus tectorum*), can dominate an ecosystem, altering fire cycles and belowground processes, and reducing herbaceous diversity (Whisenant 1990, Knapp 1996, Evans et al. 2001, Belnap et al. 2005).

Nonnatives are generally considered an undesirable component of the post-fire plant community (Allen et al. 2002, D'Antonio and Meyerson 2002). Understanding how nonnatives respond to prescribed burning and wildfire provides insight into the range of potential plant communities that may establish after fire. In this paper we will review the recent literature on nonnative response to fire in Arizona ponderosa pine forests. We will discuss the

influence of wildfire on the spread of nonnative species, the role of post-fire seeding, and provide a long-term perspective on post-wildfire, nonnative communities. We will also examine areas burned by prescribed fire, both with and without mechanical tree removal, to assess nonnative spread. Additionally, we will discuss the most common nonnative species reported in burned forests. Lastly, we will discuss topics in need of further research.

Since Arizona ponderosa pine forests have experienced a dramatic increase in fire activity in recent times, we have elected to include only research results reported in journal articles, theses, dissertations, or other research outlets since 2000. Our review is restricted to those studies that occurred in burned ponderosa pine forests of Arizona and that report, either quantitatively or qualitatively, the status of the nonnative plant community in relationship to fire. In total, we review the results of 23 studies in this article. We have elected to retain the Latin nomenclature used in the articles we have reviewed. Nativity of the various species is based on the USDA, NRCS PLANTS Database (USDA, NRCS 2009).

WILDFIRE AND NONNATIVES

Wildfires are often associated with increases in nonnative plant species (the statistics associated with the following studies are reported in Table 1). Crawford et al. (2001) reported more than 100% cumulative cover (i.e., the sum of individual species cover instead of a total cover measurement) for nonnatives in high-severity areas of three wildfires in northern Arizona. Several studies of wildfire areas on the North Rim of Grand Canyon National Park show higher amounts of nonnatives than in similar unburned areas (Laughlin et al. 2004, Laughlin and Fulé 2008). Furthermore, when compared with prescribed fires, with or without tree removal, areas burned in wildfires often contain substantially more nonnatives (Griffis et al. 2001, Bataineh et al. 2006).

Wildfire Severity and Nonnatives

Many of the differences observed in the studies mentioned above are associated with the differing severity of various fires. For example, numerous studies have documented an increased risk of invasion with increasing fire severity. Crawford et al. (2001) examined the Hochderffer, Bridger-Knoll, and Pot fires (see Fig. 1 for the locations of the wildfires mentioned in this section) 2 years after burning and found that while nonnative forbs comprised the majority of the understory community, regardless of fire severity, there was a two-fold increase in nonnative cover in high-severity burns compared to moderate-severity areas within the

same fires. The list of nonnative species presented by the authors, however, contained several species generally considered as native. Reassessing the data using more conservative yields similar trends, although they are less dramatic (Table 1). A later study of the Hochderffer Fire reported that nonnative grasses and forbs comprised 38% of the standing biomass crop (Sabo et al. 2009). Other studies have shown differential increases in nonnative forbs along a fire-severity gradient when monitored a few years after burning. Examining the Leroux Fire on the San Francisco Peaks, Dodge et al. (2008) observed an increase in Dalmatian toadflax (*Linaria dalmatica*) in the high-severity burn class. Common mullein (*Verbascum thapsus*) spread into areas burned in the Rattle Burn Fire after 2 years, with greater biomass production in the high-severity burned areas as compared to low-severity burned areas (Bataineh et al. 2006).

Not all wildfires have resulted in dramatic increases in nonnative species. In 2002, the Rodeo-Chediski Fire burned nearly 500,000 acres on the White Mountain Apache Reservation and Apache-Sitgreaves National Forest. The area was seeded with sterile hybrid wheat (*Triticum aestivum*) for erosion control. This species dominated the understory temporarily, but was uncommon by 2005. Aside from an increase in goosefoot (*Chenopodium album*) in 2004, no other nonnatives were reported to be abundant within the fire perimeter (Kuenzi 2006, Kuenzi et al. 2008). Likewise, Crawford and



Figure 1. Map of the state of Arizona showing locations of ponderosa pine forests and wildfires. Grey-shaded areas are the locations of ponderosa pine forests. Lines point to wildfire locations.

Table 1. Summary of articles reporting nonnative species quantity in post-wildfire communities in Arizona ponderosa pine forests along a fire severity gradient. The fire severity we list is consistent with the gradient listed in the article. The vegetation measurements reported in the articles and, when available, time since fire are described in the Notes column.

	High severity	Medium severity	Low severity	Unburned	Notes
Bataineh et al. 2006	41.9 kg·ha ⁻¹		17.5 kg·ha ⁻¹	3.0 kg·ha ⁻¹	Nonnative biomass 30 years after fire
Crawford et al. 2001	116%	59%		<0.5%	Percent cover from sum of individual species covers as reported in article two years after fire
	55%	30%		<0.5%	Percent cover from sum of individual species cover with revised list of nonnatives ^a
Dodge et al. 2008	30%	12%	5%	5%	Dalmatian toadflax cover ^b three years after fire
Griffis et al. 2001		7		1	Species richness, nonnative forbs only ^{bc} (# of species/375 m ² plot)
Kuenzi 2006		2%			Percent cover ^{bc}
Kuenzi et al. 2008	1.7%		0.8%		Percent cover ^b three years after fire
Laughlin et al. 2004		58%			Percent of plots containing cheatgrass in 1998 ^c , 5-11 years after fire
		42%			Percent of plots containing cheatgrass in 2001 ^c , 8-14 years after fire
Laughlin and Fulé 2008		100%		68%	Percent of plots containing cheatgrass after Powell Fire ^c ; Burned plots measured two years after fire; unburned plots measured 12 years since last fire
Leonard 2007		3.9%		0.08%	Percent cover ^c 15 years after fire
Sabo et al. 2009		>265 kg·ha ⁻¹		0 kg·ha ⁻¹	Nonnative biomass nine years after fire ^c
^a Some of the species reported in the study are generally not considered nonnative. Those species were excluded from these totals. ^b Estimated from graphs. ^c Fire severity not a component of this study. Post-fire results arbitrarily listed as medium severity					

Straka (2004) reported a slight increase in cheatgrass abundance after the Outlet Fire on the North Rim, but total cover remained low. The lack of nonnative establishment is inherently difficult to explain, but several possible causes have been proposed, including lack of seed source, pre-burn understory conditions, and unfavorable climatic conditions for nonnatives after the fire. Further research is needed on this topic.

The Influence of Time since Fire

As we have stated, most studies have shown an increase in nonnative forbs shortly after wildfire. With greater time-since-burn, however, the nonnative community consistently becomes dominated by perennial grasses. For instance, in their 30-year study of the Rattle Burn Fire, Bataineh et al. (2006) report a transition in dominance from common mullein to Kentucky bluegrass (*Poa pratensis*), although cheatgrass was also prevalent on the site. The burned area was seeded with nonnative intermediate wheatgrass (*Thinopyrum intermedium*), an indicator species of high-severity burns after 30 years. The Dude Fire in 1990 was seeded with weeping lovegrass (*Eragrostis curvula*), an African grass that comprised 93% of the herbaceous understory cover 15 years after the fire, although total cover was only 3.9% (Leonard 2007). Successional trends do not always favor nonnative perennial grasses over short-lived species. Cheatgrass can interrupt succession, often persisting as the dominant nonnative in a system for many years. On two

isolated plateaus of the North Rim, cheatgrass was prevalent more than a decade after the last fire. Laughlin et al. (2004) detected cheatgrass on approximately 50% of their study plots on Rainbow Plateau (last fire in 1993) and Powell Plateau (last fire in 1987). Cheatgrass became more abundant on both plateaus over time, occurring on 100% of the plots on Powell Plateau 2 years after the 2003 Powell Fire (Laughlin and Fulé 2008).

PRESCRIBED FIRE AND NONNATIVES

Land managers use prescribed fire to proactively reduce forest fuels, thus lowering the potential impacts of future wildfires. Increasingly, fuels reduction treatments incorporate tree thinning prior to burning to allow for recovery of the understory vegetative community and better control of the post-fire forest structure. As with wildfires, prescribed burning creates a disturbance that may facilitate the spread of nonnatives into the understory.

Prescribed burning or thinning-and-burning projects often experience less encroachment by nonnatives than wildfires, frequently due to the decreased severity of the fires. Griffis et al. (2001) compared wildfires with prescribed burns, thinned-and-burned, and unburned sites (data from studies on prescribed burning and nonnatives are presented in Table 2). They observed greater nonnative forb abundance within the area affected by wildfire than in the two management treatments and the unburned areas, which were not detectably different. Non-

Table 2. Summary of articles reporting nonnative species quantities after prescribed fire, with and without preburn thinning, in Arizona ponderosa pine forests. The vegetation measurements reported in the articles and, when available, time since fire are described in the Notes column.

	Thinned and burned	Burned only	Unburned	Notes
Bataineh et al. 2006	NA	1.6	3.0	Biomass production (kg · ha ⁻¹) 26 years after fire
Fowler et al. 2008		+35	0	Median change in density of Kentucky bluegrass <1 year after the fire
		+3	-35	Median change in density of cheatgrass <1 year after fire
Griffis et al. 2001	3	1.3	1.2	Species richness for exotic forbs, estimated from graphs (# of species/375 m ² plots)
McGlone et al. 2009	18.4%		0%	Median cover of cheatgrass 2-7 years after fire
Stoddard et al. 2008	2% H, 1% M, 0.5% L		0%	Percent cover: letter indicates level of tree remove (H = high, M = medium, L = low) 6 years after fire

native species richness did increase in burned areas, regardless of whether or not the fire was wild or managed, but the numbers were low on all sites. Sabo et al. (2009) reported that more than one-third of the aboveground biomass on a wildfire site was nonnative, while few nonnatives were detected on thinned and burned sites and none on untreated and thin-only sites. Nonnative biomass production was also lower on prescribed burns when compared to the Rattle Burn Fire (Tables 1 and 2; Bataineh et al. 2006).

Thinning and Prescribed Burning

Mechanical thinning of overstocked trees prior to burning has been shown to improve understory response when compared to only burning. Reduced competition with remaining trees and increased light infiltration play an important role in promoting the understory. Many nonnatives, however, are shade-intolerant, ruderal species. This can lead to a greater risk of invasion as light intensity increases with increased tree removal. On the South Rim of Grand Canyon National Park, Fulé et al. (2005) compared understory response to prescribed burning with two levels of thinning (full and minimal), burn-only, and untreated control plots. After 5 years, nonnative cover and species richness had increased significantly in the full-thin treatments. The minimal-thin had no change in nonnative cover but an increase in nonnative richness, while burning without thinning reduced nonnative cover. The control plots had the lowest nonnative cover and species richness. In a study at the Fort Valley Experimental Forest outside of Flagstaff, Arizona, nonnative cover and richness increased along an increasing thinning-intensity gradient the first year after treatment (Stoddard et al. 2008). After 6 years, nonnative richness remained higher in the high- and medium-thinned plots, although nonnative cover on these plots did decrease by at least half of the 1-year, post-treatment levels. Additionally, at the same location, Abella and Covington (2004) reported an increased frequency of three nonnative species – *Cirsium vulgare*, *Linaria dalmatica*, and *Verbascum thapsus* – along the thinning-intensity gradient.

Disturbance Severity and Prescribed Fire

As with wildfire, the severity of disturbances in conjunction with prescribed burning can influence the level of nonnative establishment in the post-burn community. This is of particular concern when the site is thinned prior to burning. Slash piles are a disturbance commonly associated with thinning-and-burning projects. In the Fort Valley Experimental Forest, Korb et al. (2004) observed increases in nonnative cover on slash pile scars even when soil and native seed amendments were applied. In another

north-central Arizona study, diffuse knapweed (*Centaurea diffusa*) seeds had higher germination rates in slash pile scars than in neighboring unburned areas (Wolfson et al. 2005). Moreover, germination rates of diffuse knapweed increased with increasing burn severity. Many thinned-and-burned areas of a large-scale ecological restoration project on Mt. Trumbull in northern Arizona were seriously invaded by cheatgrass in 2002 and 2003 (McGlone et al. 2009). Fuel loads at the time of burn were heavy, often resulting in high-severity fires. While many factors were involved in the spread of cheatgrass across the landscape, nonnative invasion on this site was higher than others of similar design.

DOMINANT NONNATIVE SPECIES ON BURNED SITES

Northern Arizona post-fire communities support a wide variety of species (Tables 3 and 4). The studies we reviewed report the presence of only three species that are listed as noxious in Arizona: field bindweed (*Convolvulus arvensis*), Dalmatian toadflax, and Scotch cottonthistle (*Onopordum acanthium*). Many of the nonnative species detected after fire are, however, listed as noxious in at least one western state. Several species warrant individual discussion.

Cheatgrass

Cheatgrass is an overwintering annual grass from the Mediterranean and Russian Steppe regions. During the past century it has invaded large areas of the Great Basin Desert from southern British Columbia to northern Arizona (Mack 1981, Knapp 1996). Curiously, it is only listed as a noxious weed in Colorado and Connecticut. While cheatgrass is not fire dependent, it is a fire-adapted species that can alter the frequency and intensity of indigenous fire regimes because of fine-fuel production (D'Antonio and Vitousek 1992). Cheatgrass is generally associated with lower-elevation life zones such as desert grasslands, shrublands, and pinyon-juniper woodlands. The species is, however, becoming established at higher elevations (~2000m) across a wide range of fire and other disturbance regimes (Fisher and Fulé 2004, Loeser et al. 2007, Laughlin and Fulé 2008, McGlone et al. 2009).

The ability of cheatgrass to persist as an understory dominant in ponderosa pine forests is uncertain. The species is generally shade intolerant and experiences high winter mortality, particularly in years with a long-lasting snowpack (Pierson et al. 1990, Pierson and Mack 1990). Disturbances and management activities that increase light infiltration may promote the establishment and spread of cheatgrass. Ponderosa pine forests seem to be the highest elevation life zone that can support an expanding

Table 3. List of nonnative species reported in post-wildfire understory communities in Arizona ponderosa pine forests. Latin names are consistent with the nomenclature as listed in the cited article. Common names and nativity based on USDA, NRCS PLANTS Database (USDA, NRCS 2009).

Latin name	Common name	Authors
<i>Agropyron cristatum</i>	Crested wheatgrass	Sabo et al. 2009
<i>Amaranthus</i> sp.	Pigweed	Bataineh et al. 2006
<i>Bromus inermis</i>	Smooth brome	Crawford et al. 2001, Kuenzo 2006, Kuenzi et al. 2008, Sabo et al. 2009
<i>B. japonicus</i>	Japanese brome	Kuenzi 2006, Kuenzi et al. 2008
<i>B. tectorum</i>	Cheatgrass	Crawford et al. 2001; Gildar et al. 2004; Laughlin et al. 2004, 2005; Bataineh et al. 2006; Kuenzi 2006; Dodge et al. 2008; Kuenzi et al. 2008; Laughlin and Fulé 2008; Sabo et al. 2009
<i>Chenopodium album</i>	Lambsquarter	Crawford et al. 2001, Bataineh et al. 2006, Kuenzi 2006, Kuenzi et al. 2008, Sabo et al. 2009
<i>Cirsium vulgare</i>	Bull thistle	Crawford et al. 2001, Kuenzi 2006, Dodge et al. 2008, Kuenzi et al. 2008, Sabo et al. 2009
<i>Convolvulus arvensis</i> ^a	Field bindweed	Kuenzi et al. 2008
<i>Dactylis glomerata</i>	Orchardgrass	Crawford et al. 2001, Kuenzi et al. 2008
<i>Echinochloa crus-galli</i>	Barnyardgrass	Kuenzi et al. 2008
<i>Eragrostis curvula</i>	Weeping lovegrass	Leonard 2007, Kuenzi et al. 2008
<i>E. lehmanniana</i>	Lehmann lovegrass	Kuenzi et al. 2008
<i>Erodium cicutarium</i>	Redstem stork's bill	Crawford et al. 2001, Kuenzi 2006, Dodge et al. 2008, Kuenzi et al. 2008
<i>Kochia scoparia</i>	Burning bush	Kuenzi et al. 2008
<i>Lactuca serriola</i>	Prickly lettuce	Crawford et al. 2001; Laughlin et al. 2004, 2008; Kuenzi 2006; Kuenzi et al. 2008; Sabo et al. 2009
<i>Linaria dalmatica</i> ^a	Dalmatian toadflax	Dodge et al. 2008; Sabo et al. 2009
<i>Lolium arundinaceum</i>	Tall fescue	Kuenzi et al. 2008
<i>L. perenne</i>	Perennial ryegrass	Kuenzi 2006, Kuenzi et al. 2008
<i>Malva neglecta</i>	Common mallow	Kuenzi 2006, Kuenzi et al. 2008
<i>Marrubium vulgare</i>	Horehound	Crawford et al. 2001
<i>Medicago lupulina</i>	Black medick	Crawford et al. 2001, Kuenzi et al. 2008
<i>M. sativa</i>	Alfalfa	Crawford et al. 2001
<i>Melilotus officinalis</i>	Yellow sweetclover	Crawford et al. 2001, Kuenzi et al. 2008
<i>Onopordum acanthium</i> ^a	Scotch cottonthistle	Kuenzi et al. 2008
<i>Phleum pratense</i>	Timothy	Crawford et al. 2001
<i>Poa compressa</i>	Canada bluegrass	Kuenzi 2006; Kuenzi et al. 2008
<i>P. pratensis</i> ^b	Kentucky bluegrass	Crawford et al. 2001, Bataineh et al. 2006, Kuenzi 2006, Moore et al. 2006, Kuenzi et al. 2008, Sabo et al. 2009
<i>Polygonum aviculare</i>	Prostrate knotweed	Crawford et al. 2001, Kuenzi et al. 2008
<i>P. convolvulus</i>	Black bindweed	Kuenzi et al. 2008
<i>Polypogon viridis</i>	Beardless rabbitsfoot grass	Kuenzi et al. 2008
<i>Rumex acetocella</i>	Common sheep sorrel	Bataineh et al. 2006, Kuenzi et al. 2008

Latin name	Common name	Authors
<i>R. crispus</i>	Curly dock	Kuenzi et al. 2008
<i>Salsola kali</i>	Russian thistle	Crawford et al. 2001, Sabo et al. 2009
<i>Setaria viridis</i>	Green bristlegrass	Kuenzi et al. 2008
<i>Sonchus asper</i>	Spiny sowthistle	Crawford et al. 2001, Kuenzi et al. 2008
<i>Taraxacum officinale</i>	Common dandelion	Crawford et al. 2001, Gildar et al. 2004, Kuenzi 2006, Kuenzi et al. 2008
<i>Thinopyrum intermedium</i>	Intermediate wheatgrass	Bataineh et al. 2006, Sabo et al. 2009
<i>T. ponticum</i>	Rush wheatgrass	Dodge et al. 2008
<i>Tragopogon dubius</i>	Yellow salsify	Crawford et al. 2001, Gildar et al. 2004, Laughlin et al. 2004, Kuenzi 2006, Kuenzi et al. 2008, Sabo et al. 2009
<i>Trifolium</i> sp.	Clover	Crawford et al. 2001, Dodge et al. 2008
<i>Triticum aestivum</i>	Common wheat	Kuenzi 2006, Kuenzi et al. 2008
<i>Verbascum thapsus</i>	Common mullein	Crawford et al. 2001, Bataineh et al. 2006, Kuenzi 2006, Moore et al. 2006, Dodge et al. 2008, Kuenzi et al. 2008, Sabo et al. 2009
^a Species listed in Arizona as a noxious weed.		
^b See section on <i>Poa pratensis</i> for discussion on our classification of this species as nonnative.		

Table 4. List of nonnative species reported in post-prescribed fire understory communities in Arizona ponderosa pine forests. Latin names are consistent with the nomenclature as listed in the cited article. Common names and nativity based on USDA, NRCS PLANTS Database (USDA, NRCS 2009).

Latin name	Common name	Authors
<i>Agropyron cristatum</i>	Crested wheatgrass	Fowler et al. 2008, Kuenzi et al. 2008
<i>Bromus inermis</i>	Smooth brome	Fowler et al. 2008
<i>B. japonicus</i>	Japanese brome	Fowler et al. 2008
<i>B. tectorum</i>	Cheatgrass	Fulé et al. 2002, 2005; Korb et al. 2005; Bataineh et al. 2006; Fowler et al. 2008; McGlone et al. 2009
<i>Chenopodium album</i>	Lambsquarter	Korb et al. 2005, Bataineh et al. 2006
<i>Cirsium vulgare</i>	Bull thistle	Abella and Covington 2004, Korb et al. 2004, Fowler et al. 2008, Stoddard et al. 2008
<i>Convolvulus arvensis</i> ^a	Field bindweed	Fowler et al. 2008
<i>Dactylis glomerata</i>	Orchardgrass	Korb et al. 2004, Bataineh et al. 2006, Fowler et al. 2008
<i>Erodium cicutarium</i>	Redstem stork's bill	Fowler et al. 2008
<i>Lactuca serriola</i>	Prickly lettuce	Korb et al. 2005, Fowler et al. 2008
<i>Linaria damatica</i> ^a	Dalmatian toadflax	Abella and Covington 2004; Korb et al. 2004, 2005; Stoddard et al. 2008
<i>Medicago lupulina</i>	Black medick	Fowler et al. 2008
<i>M. sativa</i>	Alfalfa	Fowler et al. 2008
<i>Melilotus officinalis</i>	Yellow sweetclover	Fowler et al. 2008
<i>Phalaris canariensis</i>	Annual canarygrass	Korb et al. 2005
<i>Phleum pratense</i>	Timothy	Fowler et al. 2008
<i>Poa pratensis</i> ^b	Kentucky bluegrass	Korb et al. 2005, Bataineh et al. 2006, Fowler et al. 2008

Latin name	Common name	Authors
<i>Polygonum aviculare</i>	Prostrate knotweed	Fowler et al. 2008
<i>Rumex acetocella</i>	Common sheep sorrel	Bataineh et al. 2006
<i>Salsola kali</i>	Russian thistle	Fowler et al. 2008
<i>Taraxacum officinale</i>	Common dandelion	Fulé et al. 2002, Fowler et al. 2008
<i>Thinopyrum intermedium</i>	Intermediate wheatgrass	Bataineh et al. 2006, Fowler et al. 2008
<i>Tragopogon dubius</i>	Yellow salsify	Fowler et al. 2008
<i>Trofolium</i> sp.	Clover	Fulé et al. 2002
<i>Verbascum thapsus</i>	Common mullein	Fulé et al. 2002, 2005; Abella and Covington 2004; Korb et al. 2004, 2005; Bataineh et al. 2006; Fowler et al. 2008; Stoddard et al. 2008

^aSpecies listed in Arizona as a noxious weed.
^bSee section on *Poa pratensis* for discussion on our classification of this species as nonnative.

population of cheatgrass under current climate conditions (Pierson and Mack 1990, Fisher and Fulé 2004).

Common Mullein

Common mullein, a biennial forb species with high seed production, enters the plant community quickly after fire, often becoming the most prevalent nonnative species (Crawford et al. 2001, Korb et al. 2004, Korb et al. 2005, Bataineh et al. 2006, Stoddard et al. 2008, Sabo et al. 2009). At the Mt. Trumbull experiment, for example, common mullein seeds comprised 60% of the post-fire seed bank (Korb et al. 2005). Studies have shown that, with time, common mullein often reduces in abundance, becoming a minor component of the post-fire community (Bataineh et al. 2006, Stoddard et al. 2008). It is possible, however, that this species could become an important understory constituent if fires burn through ponderosa pine forests more frequently. Common mullein is currently listed as noxious in Colorado and Hawaii.

Kentucky Bluegrass

Kentucky bluegrass is a rhizomatous, mat-forming grass species usually associated with lawns and turf applications. While it is commonly perceived as a nonnative, there is little agreement about its actual origin. The USDA, NRCS PLANTS Database (USDA, NRCS, 2009) lists the species as native, but the *Manual of Grasses for North America* (Grass Manual on the Web; <http://herbarium.usu.edu/webmanual>) states that the species is native to Eurasia, except for two arctic and subarctic subspecies. Studies have shown that a) the species can persist for many years after fires, and b) it does not require fire to maintain it in the system (Fisher and

Fulé 2004, Bataineh et al. 2006). Kentucky bluegrass is not listed as noxious in any state.

Dalmatian Toadflax

Only 6 of the 23 Arizona ponderosa pine post-fire studies discussed in this article had Dalmatian toadflax in the herbaceous community, and it was the dominant nonnative in only one study (Dodge et al. 2008). The paucity of occurrences of Dalmatian toadflax in fire studies, however, should not give the impression that Dalmatian toadflax is an irrelevant species. It is listed as a noxious weed in 12 states. Furthermore, it had the second highest post-fire cover of any species reported in the studies we reviewed behind lambsquarters (*Chenopodium album*) in Crawford et al. (2001).

Dalmatian toadflax is a rhizomatous perennial forb in the same plant family as common mullein (Scrophulariaceae). It is a vigorous resprouter that also produces large quantities of seeds. Dalmatian toadflax can resprout quickly after fire (Dodge et al. 2008) and can also saturate the seed bank (Korb et al. 2005), giving the species two strategies for establishing dominance in the understory community.

Other Species

Of the 43 nonnative species reported in articles reviewed here, few of them beyond the ones mentioned above are considered a serious threat to ponderosa pine ecosystems. Very common after fire are members of the Cichorieae tribe of the Asteraceae family, including common dandelion, prickly lettuce, yellow salsify (*Tragopogon dubius*), and spiny sowthistle (*Sonchus asper*). None of these species are listed as noxious weeds in any state.

Field bindweed is listed as a noxious weed in 22 states, more than any other on the post-fire sites reviewed here. It is primarily an agricultural pest

and only two studies report it occurring in post-fire communities. Bull thistle (*Cirsium vulgare*) is capable of heavily invading a burned area, although it does not seem to persist as a dominant in the understory. This scenario was observed on the 2000 Pipe Fire (a wildfire). By 2003, bull thistle was the dominant herbaceous plant on the site, but it was reduced to only a few individuals by 2007 (Ecological Restoration Institute, unpubl. data).

Another nonnative species of interest is diffuse knapweed. While this species was not reported on any of the fires cited here, there is evidence of a positive relationship between burn intensity and seed germination in ponderosa pine forests (Wolfson et al. 2005). Diffuse knapweed is common in and around Flagstaff, Arizona, providing a seed source for spread and establishment of the species in this region after fire. An extensive list of nonnative species reported in ponderosa pine forests throughout the Southwest (i.e., not limited to Arizona) can be found in Sieg et al. (2003).

FIRE AND NONNATIVES IN OTHER NORTH AMERICAN REGIONS

The interactions between fire and nonnatives in Arizona forests are similar to those seen in other ponderosa pine ecosystems in the West. In Sierra Nevada ponderosa pine and mixed-conifer forests burned in prescribed and wildfires, Keeley et al. (2003) detected significant increases in nonnatives only in high-severity fires, 3 years after burning. Cheatgrass was the dominant nonnative on these burned sites. Prescribed fires in ponderosa pine forests of the same region were heavily invaded by cheatgrass 1 year after burning (Keeley and McGinnis 2007). Cheatgrass was already established in nearby areas, so rapid invasion was not surprising. Bull thistle and cheatgrass invaded ponderosa pine forests in Oregon after prescribed burns in the fall, but not after spring burns (Kerns et al. 2006). This was positively related to the severity gradient of the fires. In Montana, thinned-and-burned ponderosa pine forests had significantly higher cover of transformer species (i.e., plants that substantively alter the ecosystem they invade [Richardson et al. 2000]) 3 years after burning than was detected in thin-only and untreated control plots (Dodson and Fiedler 2006). Logged areas in South Dakota also experienced an increase in nonnatives, but this invasion followed a cutting-severity gradient first, with burned sites having more nonnative biomass than unburned sites except in clearcut areas where the reverse was true (Wienk et al. 2004). The gradients were driven primarily by prickly lettuce, which is not usually considered a management priority.

FUTURE CONCERNS AND RESEARCH NEEDS

While nonnative species continue to be a major cause for concern in post-fire ponderosa pine forests, their impact in these ecosystems has been limited so far, especially when compared to the situation in lower-elevation ecosystems. Only three studies reported having greater than 10% cover of nonnative species in burned areas by the end of the study. Of these, two were on wildfires (Crawford et al. 2001, Dodge et al. 2008; Table 1) and one on a tree thinning and prescribed fire study (McGlone et al. 2009; Table 2). Several studies reported a species-rich, nonnative community (Crawford et al. 2001, Bataineh et al. 2006, Kuenzi 2006, Fowler et al. 2008, Kuenzi et al. 2008, McGlone et al. 2009), while other sites have widely distributed, but species poor, nonnative communities (Crawford and Straka 2004, Laughlin and Fulé 2008). This suggests that these communities may be at risk of future invasion given the proper ecological or climatic conditions. To date, however, severe invasions have been rare in Arizona ponderosa pine forests.

Mechanisms for Nonnative Invasion

The mechanisms for nonnative invasion are poorly understood. A facilitative disturbance coupled with the availability of propagules is generally viewed as essential for a successful invasion (Hobbs and Huenneke 1992, Williamson 1996), although there are documented invasions in relatively undisturbed areas (Belnap and Phillips 2001, Evans et al. 2001). Some of the studies included here conform to the classic paradigm of a severe disturbance coupled with propagule availability leading to a nonnative species invasion (Crawford et al. 2001, Dodge et al. 2008, McGlone et al. 2009). The results of several studies do not conform to this paradigm, however, with only low levels of nonnatives establishing after fire (Fulé et al. 2005, Kuenzi 2006, Kuenzi et al. 2008, Stoddard et al. 2008). Further study is needed to understand the role of disturbance, timing of climatic conditions, predisturbance management practices, and post-fire successional trends in facilitating or inhibiting the spread of nonnative plants into burned areas.

Climate Change

Climate change may alter invasion dynamics in Arizona ponderosa pine forests, as well as in many other systems and regions. Current climate change trends may lead to an increase in wildfire activity (McKenzie et al. 2004, Westerling et al. 2006). This could increase nonnative establishment and spread into forested areas. Additionally, warmer and drier conditions are predicted for the Southwest in general (Seager et al. 2007), making forests more hos-

pitabile to lower-elevation species. Bradley et al. (2009) propose that species distributions will shift to make some habitats more suitable for nonnative species, while other nonnatives will decline in some areas of their current distribution. For example, yellow starthistle (*Centaurea solstitialis*), a minor component of the understory around Flagstaff, but a serious invasive in California grasslands, has a high likelihood of retreating from the mountainous areas of Arizona with a moderate risk expanding into the grasslands of the Four Corners and many western states. Cheatgrass, on the other hand, may expand in the northern half of the western United States, but higher temperatures may actually restrict its range in the Southwest.

This suspected shift in nonnative ranges may be somewhat of an academic point when discussing ponderosa pine ecosystems since most models also predict shifts in coniferous tree distributions with climate change, including ponderosa pine forests (Shafer et al. 2001, Lenihan et al. 2003). While climate change may indeed promote nonnative species range expansion into current ponderosa pine forests, the pines may be exiting the region at the same time.

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