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Review

Post-wildfire seeding in forests of the western United States: An evidence-based review

Donna Peppin^a, Peter Z. Fulé^{a,*}, Carolyn Hull Sieg^b, Jan L. Beyers^c, Molly E. Hunter^a

^a School of Forestry and Ecological Restoration Institute, Northern Arizona University, 200 East Pine Knoll Drive, Room 116, Flagstaff, AZ 86011-5018, USA

^b USDA Forest Service, Rocky Mountain Research Station – Flagstaff Lab, 2500 South Pine Knoll Drive, Flagstaff, AZ 86001, USA

^c USDA Forest Service, Pacific Southwest Research Station, Forest Fire Laboratory, 4955 Canyon Crest Drive, Riverside, CA 92507, USA

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ABSTRACT

Broadcast seeding is one of the most widely used post-wildfire emergency response treatments intended to reduce soil erosion, increase vegetative ground cover, and minimize establishment and spread of non-native plant species. We conducted an evidence-based review to examine the effectiveness and effects of post-wildfire seeding treatments on soil stabilization, non-native species invasion, and plant community recovery in the western U.S. We reviewed 94 scientific papers and agency monitoring reports identified using a systematic search protocol. As sampling designs have become more rigorous in recent years, evidence that seeding is effective in reducing erosion has decreased. Of highest and high quality studies evaluating soil erosion, 92% (11 of 12) were published since 2000, none of which showed an effective result. Before 2000, the majority of the studies (71%) fell into the lowest quality categories, of which 72% showed seeding to be effective. The majority of studies (20 of 27, 74%) evaluating soil erosion in seeded versus unseeded controls showed that seeding did not reduce erosion relative to unseeded controls. Even when seeding significantly increased vegetative cover, seeded sites rarely supported plant cover levels considered sufficient to stabilize soils within the first and second year post-wildfire. Of the 11 studies evaluating seeding effectiveness for curtailing invasions of non-native plant species, an almost equal percentage found seeding treatments to be either effective (54%, 6 studies) or ineffective (45%, 5 studies). However, the majority of effective and ineffective treatments (83% and 80%, respectively) used non-native species. Sixteen of 26 studies (62%) evaluating seeding effects on plant communities reported that seeding suppressed recovery of native plants, although data on long-term impacts of this reduction are limited. The literature suggests that post-wildfire seeding does little to protect soil in the short-term, has equivocal effect on invasion of non-native species, and can have negative effects on native vegetation recovery, although long-term studies are needed to assess lasting impacts of seeded species.

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Contents

| | |
|--|-----|
| 1. Introduction | 573 |
| 2. Methods | 574 |
| 3. Results and discussion | 575 |
| 3.1. Does seeding after severe forest fires in the western United States reduce soil erosion? | 575 |
| 3.2. Does seeding reduce non-native species invasions in severely burned forest land in the western United States? | 578 |
| 3.3. Does seeding after severe forest fires in the western United States affect native plant community recovery? | 578 |
| 4. Conclusions | 581 |
| Acknowledgments | 581 |
| Appendix A. Evidence-based review references (with quality of evidence ratings) | 581 |
| References | 584 |

* Corresponding author at: P.O. Box 15081, Flagstaff, AZ 86011, USA.

Tel.: +1 928 523 1463; fax: +1 928 523 0296.

E-mail addresses: donna.peppin@nau.edu (D. Peppin), Pete.Fule@nau.edu (P.Z. Fulé), csieg@fs.fed.us (C.H. Sieg), jbeyers@fs.fed.us (J.L. Beyers), Molly.Hunter@nau.edu (M.E. Hunter).

1. Introduction

By consuming protective vegetation and litter cover, high-intensity wildfires frequently result in greatly increased erosion, runoff, and sediment transport that can threaten downstream

resources and infrastructure (DeBano et al., 1998; Neary et al., 2005). The increased availability of light and nutrients after wildfire also creates conditions favorable for invasion of non-native plant species (DeBano et al., 1998; Crawford et al., 2001; Keeley et al., 2003; Wang and Kembell, 2005; Freeman et al., 2007). Land management agencies in the United States are required to assess burned areas and to prescribe emergency watershed-rehabilitation measures when and where deemed necessary to minimize threats to life and property or to stabilize and prevent further unacceptable degradation to natural and cultural resources resulting from the effects of a wildfire (USDA, 2004; USDI, 2006). Aerial seeding of grasses, typically non-native annuals or short-lived perennials, has been the most commonly used post-wildfire rehabilitation treatment to establish ground cover for erosion control and reduce non-native species invasions (Robichaud et al., 2000; Beyers, 2004).

Federal policy in the U.S. currently mandates use of seed from native species for post-wildfire rehabilitation when available and economically feasible (Richards et al., 1998). Although the use of native species has increased (Beyers, 2004; Wolfson and Sieg, *in press*), high costs and inadequate availability often limit inclusion of native plants in post-wildfire seedings. Furthermore, a vague definition of the term “native” has led to inconsistent interpretations regarding the functional types and geographic origins of native species used (Richards et al., 1998). Despite ongoing debates over the efficacy of post-wildfire seeding and potential negative impacts on natural plant community recovery, seeding remains a widely used stabilization treatment in forested ecosystems throughout the western U.S. (Wolfson and Sieg, *in press*).

In 2000, Robichaud et al. reviewed the effectiveness and impacts of the entire suite of burned area rehabilitation treatments used on U.S. Forest Service land, including post-fire seeding. Beyers (2004) published a review specific to post-wildfire seeding, but a good part of the conclusions were drawn from studies occurring in chaparral. Almost all of the seeding projects reviewed in these two publications used non-native species. Since these reviews appeared, several developments have altered the context of post-wildfire seeding in the western U.S. These include increased research and quantitative monitoring on post-wildfire seeding, largely in response to information needs highlighted in the review publications; increased use of and allocation of funds for native seed mixes (Wolfson and Sieg, *in press*); stronger policy direction for the use of locally adapted and genetically appropriate seed sources (seed sources adapted to local site conditions and genetically compatible with existing plant populations) (GAO, 2003; Rogers and Montalvo, 2004; USDA, 2006); and increasing size and severity of wildfires across the western U.S. (McKenzie et al., 2004; Westerling et al., 2006; Littell et al., 2009). The time is ripe for a new analysis of the effectiveness and ecological impacts of post-wildfire seeding.

To examine the effectiveness and effects of post-wildfire seeding on soils and native plant communities in forested ecosystems across the western U.S., we conducted a systematic review of scientific literature and unpublished reports. We addressed three questions pertaining to post-wildfire seeding treatment effectiveness and effects: (1) Does seeding after severe forest fires reduce soil erosion? (2) Is seeding effective at reducing non-native plant invasion into burned areas? and (3) Does post-wildfire seeding affect native plant community recovery? The systematic review methodology is relatively new in natural resource disciplines but has been widely used in medical sciences (Fazey et al., 2005; Pullin and Stewart, 2006). This methodology follows a rigorous, predetermined protocol which greatly improves traditional narratives or “vote-counting” reviews by reducing bias and enhancing the accuracy, reliability, and usefulness of the review (Gates, 2002). Both land managers and the broader scientific community should benefit from the information contained within the review.

Table 1

Inclusion categories and specified inclusion criteria used when evaluating post-wildfire studies to be included in the review.

| Inclusion category | Specified inclusion criteria |
|--------------------|--|
| Subject(s) studied | Seeding studies conducted in forests burned by wildfire in the western U.S. since 1970. Experimental seeding studies in controlled burns, such as prescribed fires, were also included if the information was deemed relevant to post-wildfire seeding. Non-wildfire seeding data were summarized separately from wildfire data. |
| Treatment(s) | Seeding herbaceous plant or shrub seed alone or in combination with other post-wildfire rehabilitation activities such as mulching, fertilizing, soil ripping, and log erosion barriers. |
| Outcome(s) | Soil stabilization attributes, such as runoff, surface erosion, and sediment yield, and change in plant community attributes, such as cover, richness, diversity, biomass, and composition of native and non-native herbaceous plants, shrubs, and trees. |

2. Methods

We conducted our formal systematic review in stages established by Pullin and Stewart (2006): (1) question formulation, (2) protocol formation and search strategy, (3) data extraction, and (4) analysis. The review team drafted primary and secondary study questions, which were further refined by managers, scientists, and outside experts. For this review, we defined forested ecosystems as those dominated by coniferous and/or deciduous trees occurring at elevations above grasslands, pinyon-juniper woodlands, or chaparral vegetation in the western U.S.

We produced a review protocol to guide key decisions: (1) search, inclusion, and rejection criteria; (2) extracting evidence; and (3) comparing evidence. We submitted our review protocol to The Centre for Evidence-Based Conservation (www.cebc.bangor.ac.uk/; Systematic Review No. 60), an international organization that hosts systematic review protocols online and facilitates review by a worldwide audience, for independent review.

We searched online databases (JSTOR, Google Scholar, Forest Science Database, Ingenta, Web of Science, AGRICOLA), online government collections, and electronic university libraries using combinations of key search terms: seeding AND fire, seeding AND burn, seeding AND wildfire, seeding AND erosion, and seeding AND native species. Refereed journal articles, peer-reviewed reports (such as government documents and conference proceedings), theses and dissertations, and unpublished literature were considered. Potential studies were then evaluated for inclusion according to specified criteria (Table 1). All potentially relevant publications were imported into a database, then examined by the senior author for final inclusion decisions.

For consistency, each paper was reviewed by two members of the review panel. Reviewers did not evaluate papers they authored. Both qualitative and quantitative data were extracted. The final review database was then reviewed by the senior author to locate any inconsistencies in recorded data, which were discussed with panel members and resolved.

We assigned “quality of evidence” ratings (standard terminology used in systematic reviews and based on objective criteria; Baker and Shinneman, 2004; Pullin and Stewart, 2006) for each study based on experimental design and statistical robustness (Table 2). Statistically robust data from replicated randomized and controlled experiments were judged to be of “highest” quality; whereas unreplicated, uncontrolled, qualitative data had “lowest” quality of evidence. We evaluated post-wildfire seeding effective-

Table 2
Criteria for rating the quality of evidence presented in the post-wildfire papers reviewed (occurring in forested ecosystems in the western U.S.) and their respective categories.

| Study design ^a and statistical robustness | Quality of evidence |
|--|---------------------|
| Statistically robust evidence obtained from replicated randomized and controlled experiments with sampling occurring after seeding treatments in areas burned by wildfire, prescribed burn, or slash pile burning | Highest |
| Unreplicated, controlled, observational or monitoring report (multiple locations); Before After Control Impact study (BACI) with reliable quantitative data from sampling occurring after seeding treatments in areas burned by wildfire, prescribed burn, or slash pile burning; peer-reviewed reviews on post-wildfire seeding | High |
| Unreplicated, controlled, observational or monitoring report (single location) with reliable quantitative data | Medium |
| Unreplicated, uncontrolled, observational or monitoring report; quantitative data | Low |
| Unreplicated, uncontrolled, qualitative data; anecdotal observation; expert opinion; or review of post-wildfire seeding (not peer-reviewed with qualitative data) | Lowest |

^a Major study design categories included: replicated randomized experiment, observational (multiple location case study), observational (single location case study), monitoring report with quantitative data, monitoring report with qualitative data, BACI, review paper, and expert opinion.

ness based on the treatment's effectiveness in reducing: (1) erosion and sedimentation; (2) non-native species invasion; and (3) effects on native plant community recovery. Studies were examined for overall seeding treatment effectiveness or ecosystem impacts in each category (Table 3). When available, quantitative data from seeded and unseeded treatments were compared. Some studies had multiple sites; we made comparisons based on the number of sites rather than the total number of publications. Each study or individual site within a study was given an effectiveness rating (Table 4). Studies/sites rated as "no difference in effectiveness" were not statistically or perceivably different in their effectiveness, whereas those judged to be "ineffective" were counter-productive in their effectiveness to a specified impact category (e.g., effect was opposite of that intended).

For this review, we used descriptive statistics to explore relationships between post-wildfire seeding treatments and associated variables as well as the influence of time since fire. We divided relevant papers into ecoregions (Bailey, 1983; Table 5) for analysis of geographic influences. We characterized the types of plant species seeded as non-native or native. Nativity was assigned according to the U.S. Department of Agriculture, Natural Resource Conservation Service Plants Database (NRCS, 2010).

Table 3
Measurements reported in papers examining post-wildfire seeding in forested ecosystems in the western U.S. that were used to judge overall seeding treatment effectiveness or ecosystem impacts.

| Category | Measures of effectiveness/impacts |
|------------------------------|---|
| Erosion control | Decreased sediment yield, surface erosion, or runoff |
| Non-native species | Decreased cover, frequency, density, or species richness of non-native invasive plants |
| Effects on plant communities | Negative changes to native plant community attributes such as cover, biomass, composition, frequency, species richness, and density |

Table 4
Criteria for rating seeding treatment effectiveness and their respective categories in the post-wildfire studies reviewed (occurring in forested ecosystems in the western U.S.).

| Criteria for rating seeding treatment effectiveness | Effectiveness rating |
|--|--------------------------------|
| Sufficient evidence exists to conclude that seeding was statistically or perceivably effective in decreasing erosion, increasing cover, or reducing non-native species invasions without negative effects | Effective |
| Sufficient evidence exists to conclude that seeding was effective under some but not all circumstances or seeding was effective, but with potentially negative ecosystem impacts | Minimal effectiveness |
| Sufficient information exists to conclude that seeding treatments in treated and untreated controls were not statistically or perceivably different in their effectiveness for increasing cover, reducing erosion, and/or reducing non-native species invasions | No difference in effectiveness |
| Sufficient evidence exists to conclude that seeding was statistically or perceivably different in effectiveness, where treatments were counter-productive in their effectiveness (e.g. effect was opposite of what was intended); potentially negative ecosystem impacts exist | Ineffective |

For each review question, we draw conclusions (when possible) based on data from 1970 to 1999, including papers previously reviewed by Robichaud et al. (2000), and on data published from 2000 to 2009. Given the policy shifts, we expected the most recent studies to include more use of native species in seed mixes and address invasive plant control in burned forests.

3. Results and discussion

Approximately 19,455 studies were identified through the literature search, of which 94 were considered relevant after applying inclusion criteria (Table 1) and receiving full review (see Appendix A). Within this dataset ($n=94$), replicated and randomized experiments made up the largest category (19%, Fig. 1). In the more recent period, 2000–2009 ($n=57$), there was a greater proportion of replicated randomized experiments (46%), review papers (29%), and expert opinions (27%) compared to 1970–1999 ($n=37$) (Fig. 1). Using quality of evidence criteria, during the time period between 1970 and 1999, 6 studies (16%) were of highest quality, 5 studies (14%) were high quality, 4 studies (11%) were medium quality, and the majority (60%) were in the low and lowest quality category (Fig. 2). The proportion of studies in these categories changed slightly for the 2000–2009 papers, with the greatest increase in the high quality of evidence category (28%).

3.1. Does seeding after severe forest fires in the western United States reduce soil erosion?

Twenty-seven studies provided evidence regarding post-wildfire seeding effects on soil erosion in the western U.S. Authors defined erosion control in terms of decreases in sediment yield, runoff, or surface erosion. Using our effectiveness classification (Table 4), 9 of the 27 studies (33%) showed seeding to be effective, 7 (26%) showed minimal effectiveness or ineffectiveness, and 4 (15%) showed no difference in effectiveness of seeding in reducing erosion. However, the evidence for seeding effectiveness drops substantially when quality of evidence criteria (Table 2) are considered: none of the four studies with highest quality evidence found seeding to be effective or even minimally effective in reducing soil erosion when compared to unseeded control plots. For exam-

Table 5
Number of sites in published post-wildfire studies conducted in forested ecosystems in the western U.S. reporting measures of seeding “success” by ecoregion (Bailey, 1983) during the first 2 years following fire.

| Ecoregion name | Sites showing seeding significantly increased cover | % of sites showing >30 cover (no. of sites) | | % of sites showing >60% cover (no. of sites) | | Sites showing erosion measurements | Those showing seeding significantly reduced erosion |
|---------------------------------------|---|---|----------|--|----------|------------------------------------|---|
| | | Seeded | Unseeded | Seeded | Unseeded | | |
| Post-wildfire year 1 | | | | | | | |
| Marine Regime Mountains | | | | | | | |
| 6 | 3 | 33 (2) | 17 (1) | 0 | 0 | 5 | 0 |
| Temperate Steppe Regime Mountains | | | | | | | |
| 8 | 0 | 50 (4) | 50 (4) | 0 | 0 | 4 | 0 |
| Tropical/Subtropical Regime Mountains | | | | | | | |
| 3 | 0 | 100 (3) | 100 (3) | 0 | 0 | 0 | – |
| Mediterranean Regime Mountains | | | | | | | |
| 12 | 9 | 58 (7) | 8 (1) | 33 (4) | 0 | 3 | 0 |
| Combined | | | | | | | |
| 29 | 12 | 55 (16) | 31 (9) | 14 (4) | 0 | 12 | 0 |
| Post-wildfire year 2 | | | | | | | |
| Marine Regime Mountains | | | | | | | |
| 4 | 1 | 100 (4) | 75 (3) | 0 | 0 | 5 | 0 |
| Temperate Steppe Regime Mountains | | | | | | | |
| 7 | 0 | 71 (5) | 71 (5) | 0 | 14 (1) | 5 | 1 |
| Mediterranean Regime Mountains | | | | | | | |
| 7 | 6 | 86 (6) | 14 (1) | 71 (5) | 0 | 0 | 0 |
| Combined | | | | | | | |
| 18 | 7 | 83 (15) | 50 (9) | 28 (5) | 6 (1) | 10 | 1 |

ple, Robichaud et al. (2006), in a study conducted in north-central Washington, used a randomized block design of four plots with controls, replicated eight times, to compare the effects of seeding with winter wheat (*Triticum aestivum* L.) and fertilizing on post-wildfire erosion rates. They found no reduction in erosion rates for seeding or fertilization treatments, alone or in combination, at any time during the 4-year study. Five of the eight studies (63%) with high quality evidence found seeding to be ineffective, while two reported minimal effectiveness. The remaining study reported that seeding (seeded species unknown) was effective for erosion reduction only in combination with mulching and log erosion barriers on a fire in southwestern Colorado (DeWolfe et al., 2008).

More evidence for seeding effectiveness was reported in studies with lower quality evidence. One of three medium quality studies, three of four low quality studies, and all eight lowest quality studies found seeding to be effective or minimally effective in reducing erosion. For example, in a publication considered to have lowest quality evidence, two subjectively chosen study areas were set up within a single burned area in the Black Hills, South Dakota, each with eight plots to assess sedimentation and runoff (Orr, 1970). The study found that a mixture of seeded non-native grass and legume species dominated the cover at both sites throughout the study and suggested that neither site would have reached a 60% ground-cover requirement for minimum soil stability within 4

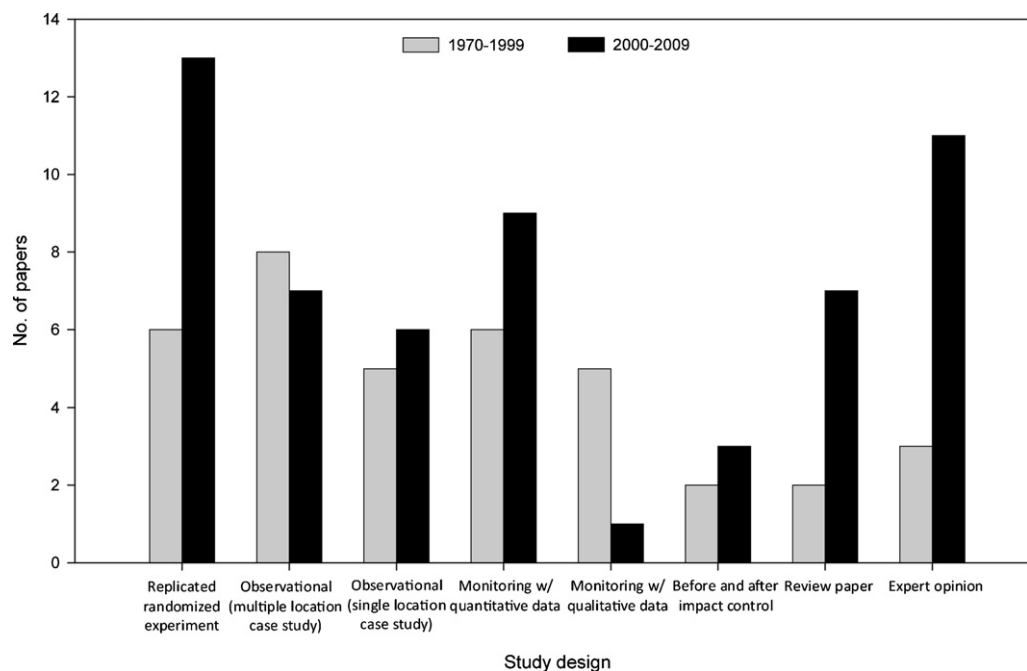


Fig. 1. The number of papers by study design category for post-wildfire studies reviewed (occurring in forested ecosystems in the western U.S.) from 1970 to 1999 (37 papers) and those since 2000 (57 papers).

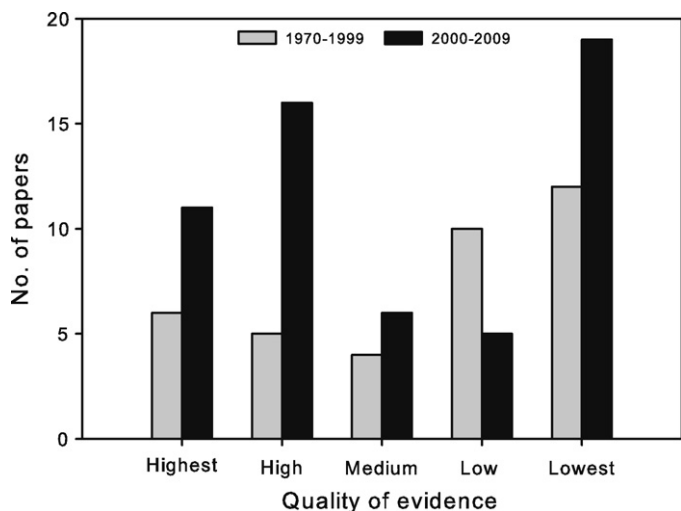


Fig. 2. The number of papers by quality of evidence for post-wildfire studies reviewed (occurring in forested ecosystems in the western U.S.) from 1970 to 1999 (37 papers) and since 2000 (57 papers).

years without seeding; however, no unseeded sites were evaluated (Orr, 1970).

As sampling designs have become more rigorous in recent years, evidence that seeding is effective in reducing erosion has decreased. None of the 16 studies published since 2000 concluded that seeding was effective or minimally effective in reducing erosion compared to controls, whereas seven of 11 studies published before 2000 found seeding to be in those categories. Only one of the earlier studies met the criteria for highest or high quality evidence, while 11 of the studies since 2000 did.

Only nine of the 27 studies used direct measures of sediment yield from 30 seeded and unseeded sites to assess post-wildfire seeding effectiveness. While seeded sites tended to produce less sediment than unseeded sites the first year after fire (Fig. 3), only seven of the sites showed a statistically significant decrease in erosion on seeded relative to unseeded sites. This largely non-significant trend toward sediment yield reduction was less apparent in measurements from the second year post-wildfire and essentially disappeared by the third and subsequent years. Fewer studies quantified sediment yield in seeded and unseeded plots

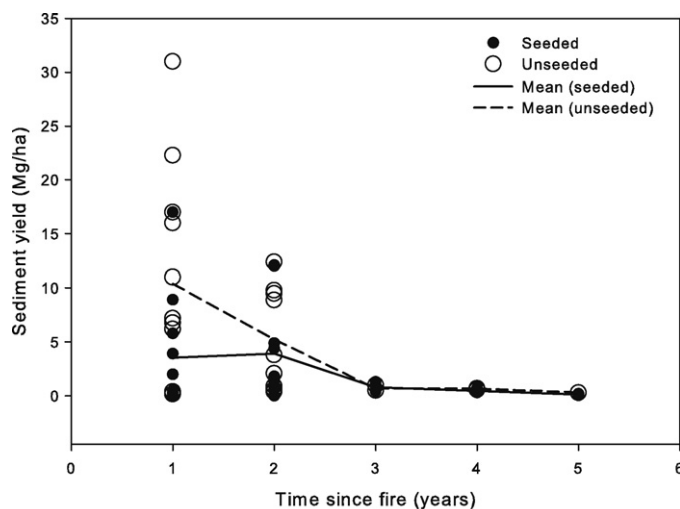


Fig. 3. Amount of sediment yield versus time since fire in seeded plots and unseeded plots (data from 30 sites contained in nine studies assessing post-wildfire seeding effectiveness for soil erosion in forested ecosystems in the western U.S.).

after 2 years, with only three studies continuing measurement into the third and fourth year after fire and two in year 5, making assessment of overall trends difficult. The studies continuing measurements into the third to fifth year after fire showed little sediment movement in either seeded or unseeded sites (Fig. 3), indicating that slopes had largely stabilized. More longer term studies are needed to confirm the trend that slopes are largely stabilized by the third year post-wildfire. If true, this would support using only very short-lived plant species for post-wildfire seeding.

Sediment movement is strongly related to the amount of cover on a hillslope (Robichaud et al., 2006; Rough, 2007). Because so few studies reported actual erosion measurements, we also used vegetation cover as an indicator of seeding “success” for potential erosion control effectiveness (Dadkhah and Gifford, 1980; Bruggink, 2007). We included studies from the first and second year after fire that compared seeded treatments to unseeded plots in this analysis. As was done in Robichaud et al. (2000) and Beyers (2004), we used two levels of cover to indicate the potential for seeding to reduce erosion. Cover between 30 and 60% was regarded as partially effective at reducing erosion, and cover >60%, which has been found to allow negligible sediment movement, was considered to be effective (Noble, 1965; Orr, 1970).

Comparing cover measurements between seeded and unseeded plots from 20 studies containing a total of 29 study sites, we found that 12 sites (41%) had significantly greater total plant cover on seeded plots by the end of the first year after fire. Sixteen seeded sites (55%) had >30% total plant cover in the first year after fire, compared to only nine unseeded sites (31%; Table 5). Another four seeded sites (14%) had >60% total plant cover after the first-year post-wildfire compared to none of the unseeded sites. However, of the 12 sites where erosion was measured along with cover, none showed that seeding significantly reduced erosion in the first year after fire.

In the second year after fire, seeded sites were nearly four times more likely to be stabilized than untreated sites based on percent cover (Table 5). Second-year seeded sites had greater total cover than did unseeded sites in 39% of the cases. Fifteen seeded sites (83%) had plant cover that exceeded 30%, compared to only half (9 sites) of unseeded sites. Five seeded sites (28%) had adequate cover (>60%) to reduce soil erosion to negligible amounts, compared to only one unseeded site (6%). Despite these cover findings, only one of the 10 studies measuring erosion in the second year showed that seeding significantly reduced erosion. It appears that greater cover does not always produce less erosion. This could be due to the timing of erosion-producing events – during winter or summer thunderstorms – relative to when plant and ground cover is measured, typically at the end of the growing season. New studies that quantify cover and erosion events concurrently could help address this conundrum. A main goal of post-wildfire stabilization treatments is to reduce soil erosion in the year immediately following a fire (Robichaud et al., 2000). However, the ability of seeding to effectively reduce erosion within the first and even second year post-wildfire depends largely of amount and timing of precipitation events, not percent cover, as shown by minimal support for the cover thresholds used.

Authors of all four review papers agreed that research to date has failed to show any notable relationship between establishment of vegetative cover and reduction of erosion within the first year after fire (Beschta et al., 2004; Beyers, 2004; Wolfson and Sieg, in press; Robichaud et al., 2000). This conclusion is not surprising as the majority of sediment movement often occurs before plant cover is established (Robichaud et al., 2000). Interestingly, our review suggests that seeding was more likely to increase plant cover and therefore potentially reduce soil erosion in the Marine and Mediterranean Regime Mountain ecoregions than in Temper-

ate Steppe Regime Mountains ecoregion (Table 5; see Bailey, 1983 for ecoregion boundaries).

In the Intermountain West and Rocky Mountains (Temperate Steppe Regime Mountains), high-intensity short-duration rainfall events often occur shortly after severe wildfires (Robichaud et al., 2000). Watersheds within this region are therefore vulnerable to heavy erosion immediately following fire (Wagenbrenner et al., 2006; Kunze and Stednick, 2006; Rough, 2007). In contrast, forests of the Mediterranean and Marine Regimes (California and the Pacific Northwest) receive most precipitation during the winter months as snow or are subjected to prolonged periods of rainfall, allowing seeded species to germinate under better conditions (Anderson and Brooks, 1975; Roby, 1989; Amaranthus et al., 1993; Robichaud et al., 2006; Peterson et al., 2007). Therefore, seeding may be a more appropriate rehabilitation action in Mediterranean and Marine Regimes than in Temperate Steppe Regime Mountains.

Several studies provide evidence that seeding for erosion control may be more effective when done in concert with other treatments (Maloney et al., 1995; Meyer et al., 2001; Earles et al., 2005; DeWolfe et al., 2008), although other studies suggest that mulch treatments alone may be more effective than seeding in reducing erosion (Wagenbrenner et al., 2006; Groen and Woods, 2008; MacDonald and Larsen, 2009). For example, in a study conducted in northwestern Montana, Groen and Woods (2008) found straw mulch application at a rate of 2.24 Mg/ha resulted in 100% ground cover and reduced rainsplash erosion by 87% in small test plots, whereas an aerially seeded mixture of native grasses failed to provide enough ground cover to reduce the erosion rate relative to untreated plots. In studies conducted in Colorado's Front Range, MacDonald and Larsen (2009) and Wagenbrenner et al. (2006) also found straw mulch to be more effective than other treatments (seeding alone, seeding and mulching, contour-felled logs, hydro-mulch, and polyacrylamide) for reducing soil erosion following wildfires. Seeded species in MacDonald and Larsen (2009) included native cultivars and sterile cereal grains, while Wagenbrenner et al. (2006) tested a mixture of non-natives plus sterile and non-sterile cereal grains. In sum, the reviewed papers suggest that seeding may be more effective when used with other erosion control measures, but mulching alone can provide as much or more cover than all other treatment combined. Conversely, mulching can potentially harm native ecosystems by inhibiting native species recovery (Schuman et al., 1991; Bakker et al., 2003; Kruse et al., 2004) and introducing non-native species through contaminated straw bales (Kruse et al., 2004). The long-term consequences of mulching are largely unknown and a critical area for future research.

3.2. Does seeding reduce non-native species invasions in severely burned forest land in the western United States?

Post-wildfire seeding treatments are often designed to mitigate or prevent invasions of undesirable non-native species (Robichaud et al., 2000; USDA, 2004). Seeded grasses are thought to combat non-native species due to their quick growth, capturing resources ahead of invading non-native species (Robichaud et al., 2000; Grime, 2001; Beyers, 2004). The 11 studies with direct data on seeding effects on non-native species abundance were split: six studies (55%) showed seeding to be effective in reducing non-natives, whereas five studies (45%) showed it was not. The majority of highest quality studies (three of five) showed seeding to be effective for reducing non-natives; however, two of those were conducted in prescribed burn or slash pile burned areas. Only one of three studies of high quality showed seeding to be effective for reducing non-native species.

All of the papers on the effectiveness of seeding for reducing non-native species invasion in forested ecosystems were published since 1998, with more than half since 2004. This likely reflects the

increased interest in this kind of treatment by land management agencies. Further research and longer term quantitative monitoring are needed to assess more thoroughly the effectiveness of seeding to prevent non-native species invasion after fire.

Successful exclusion of non-natives often resulted when seeded species produced high cover (Barclay et al., 2004; Keeley, 2004), while ineffective studies generally showed no difference in total cover on seeded and unseeded sites (Sexton, 1998; Hunter and Omi, 2006; Stella et al., in press). Of the six studies showing seeding to be effective, five included non-native annual species in the seeding treatments. Thus, successful suppression of non-seeded invaders appears to result from the competitive advantage of other (seeded) non-native species (Schoennagel and Waller, 1999; Barclay et al., 2004; Keeley, 2004). These same studies and others showed successful seeded species also displaced native species (Sexton, 1998; Schoennagel and Waller, 1999; Barclay et al., 2004; Keeley, 2004; Logar, 2006), in some cases through extended persistence in the seeded sites (Sexton, 1998; Barclay et al., 2004; Hunter et al., 2006). Two studies found that seed mixes were contaminated with exotics (Sexton, 1998; Hunter et al., 2006). It appears that seeding to reduce negative impacts of invading non-native species on post-wildfire vegetation recovery may actually end up replacing one (or more) competitive non-native species with another, thus being counter-productive to the objective of the treatment.

Few studies have investigated the use of native species for reducing non-native species invasion, and only one of the three using native seed was conducted after a wildfire. Stella et al. (in press) found that non-native species richness and abundance did not differ among seeding treatments incorporating non-native and native species mixes on three high-severity wildfires in Arizona. The other studies were conducted following a prescribed burn in northwestern Arizona (Springer et al., 2001) and following slash pile burning in northern Arizona (Korb et al., 2004). Springer et al. (2001) found that seeding certified "weed-free" native seeds was ineffective in reducing non-natives, whereas Korb et al. (2004) noted that seeding native species was effective only with the addition of soil amendments. Research on post-fire seeding with native species is clearly limited. Recently, debates over the use of "native" species during rehabilitation and restoration have arisen based on concern that using native seed from distant sources may contaminate local gene pools (Huenneke, 1991; Schmid, 1994; Linhart, 1995; Hufford and Mazer, 2003; Rogers and Montalvo, 2004); however, limited research has actually been conducted on the topic. With increased incorporation of native species in post-fire seeding treatments, research investigating the effectiveness and effects of using native species is warranted.

3.3. Does seeding after severe forest fires in the western United States affect native plant community recovery?

There is substantial evidence in older literature that seeded species may suppress recovery of native herbaceous species and woody plant seedlings (Beyers, 2004). Of the 26 papers with data on post-wildfire seeding effects on native plant recovery reviewed for this study, the majority (16 studies, 62%) found lower cover of native species on seeded plots compared to unseeded plots, while five studies (19%) showed greater native species cover on seeded plots.

Of the highest (three out of six studies) and high quality (two out of five studies) evidence studies finding a reduction of native plant cover with seeding (five studies), three suggested that seeding could have persistent effects on post-wildfire vegetation recovery. For example, Stella (2009) found that annual and biennial native forbs were significantly reduced in seeded treatments (native and annual non-native mix) compared to unseeded treatments the first year after fire; this reduction persisted into the second year even

though the cover of seeded species declined. Another southwestern U.S. study found a similar effect of seeding annual ryegrass (*Lolium perenne* ssp. *multiflorum* (Lam.) Husnot) on native forbs (Barclay et al., 2004): cover of native forbs in unseeded areas increased from year 1 to year 2, but native forb cover in seeded areas remained constant even though ryegrass cover declined. The third study, conducted in the eastern Cascades, Washington, USA, showed a reduction of native early-successional species and fire-dependent colonizers as a result of high frequency and cover of seeded non-natives. The researchers suggested that seeding effects could therefore alter native plant communities well beyond the life of the seeded species (Schoennagel and Waller, 1999). Any persistent effects seeding may have on native plant recovery can only be determined through analysis of longer term monitoring data sets.

In contrast, two studies with highest and high quality evidence found that seeding enhanced native plant cover (Springer et al., 2001; Hunter and Omi, 2006). In a study conducted by Springer et al. (2001), native species were seeded solely which may have contributed to increased native species cover. Hunter and Omi (2006) examined how seeded species (a mixture of native cultivars and non-native annual grasses) and native grasses responded to increased availability of soil nitrogen and light after the Cerro Grande Fire in New Mexico. They found that cover of native species (those not seeded during post-fire rehabilitation efforts) increased over a 4-year period in seeded areas of low fire severity and did not differ between seeded and unseeded areas of high fire severity, although seeded grass cover remained high. Results from these studies indicate that what species are seeded and fire severity play a major role in determining any impacts seeded species may have on native plant communities.

Both seeded species and native plant cover are highly influenced by post-wildfire precipitation. When unfavorable conditions (e.g., low precipitation) occur, seeding often has no effect on native species cover and/or recovery due to low success rates (Robichaud et al., 2006; Wagenbrenner et al., 2006; Peterson et al., 2007). In contrast, under favorable conditions seeded species can rapidly dominate the post-wildfire environment, which in turn may lead to low first-year native plant recruitment and subsequent reductions in native species over time. However, one long-term study revealed that 31 years after a fire in north-central Washington, non-native cultivars which dominated seeded sites initially were completely replaced by a diverse mixture of native graminoids, forbs, shrubs and trees (Roche et al., 2008). This study suggests that non-native grasses seeded after wildfires do not always have persistent effects on native plant communities, but long-term datasets like this one are rare.

Seeding treatment performance and effects are related to length of time since fire (Robichaud and Elliot, 2006; Rough, 2007). Cover data from 15 studies containing 57 different study sites showed decreased seeded cover relative to control plot cover with increasing time since fire (Fig. 4). Total cover on seeded plots was more variable but only slightly higher on average than total cover on control sites for 2 years post-wildfire; after 2 years, control cover was consistently greater than seeded cover, although the number of studies continuing measurements beyond this timeframe was limited. Of 13 sites with greater cover on seeded than unseeded sites in the first and/or second year post-wildfire, the majority (10 sites) occurred in ecoregions characterized by favorable rainfall intensity, amounts, and timing. In addition, in all of these sites annual cereal grains or non-native perennial grass species were either seeded alone (eight sites) or as a predominant proportion of a mix with natives cultivars and legumes (five sites) (Anderson and Brooks, 1975; Griffin, 1982; Amaranthus, 1989; Amaranthus et al., 1993; Holzworth et al., 2003; Keeley, 2004; Logar, 2006; Roche et al., 2008). These results suggest that seeded species, in particular annual cereal grains, may exit the system quickly (Kuenzi et al.,

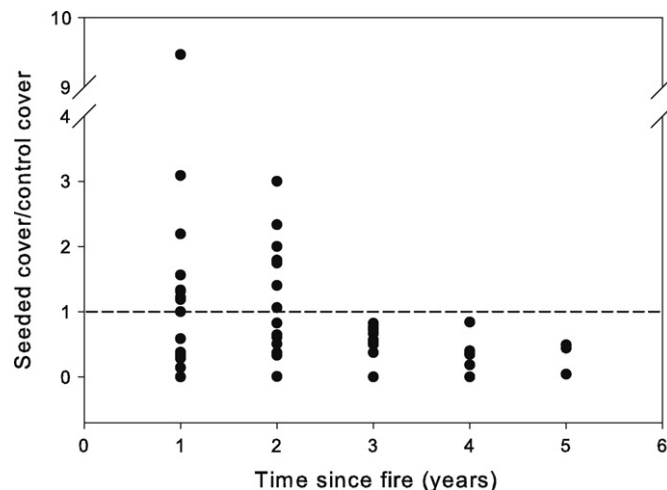


Fig. 4. Ratio between seeded and control cover estimates versus time since fire in years (data from 57 sites contained in 15 studies assessing post-wildfire seeding treatment performance in forested ecosystems in the western U.S.). Ratios greater than one have greater seeded cover than control cover.

2008) or be outcompeted by native or naturalized species after 2 years. However, data beyond 2 years from areas seeded with annual cereal grains are rare, so studies quantifying their ability for rapid die-off are limited. In addition, the lack of long-term studies compromises assessment of overall trends in post-wildfire effects on plant communities, something that only long-term data sets can develop.

Based on data from all 57 sites, by 4 years after fire both seeded and unseeded sites supported approximately 45% total plant cover (seeded + unseeded species) and only about 40% total plant cover after 5 years (Fig. 5). Seeded cover (seeded species only) was relatively high for the first 3 years after fire (about the same as control cover (unseeded) during the first 2 years) but declined substantially to 13% and 14% in years 4 and 5, respectively. The higher initial seeded cover suggests that one of the major goals of post-wildfire rehabilitation was being effectively met: seeded species established quickly and lasted for a few years, then decreased relative to other species. However, total cover in seeded sites and controls was nearly identical by years 4 and 5, suggesting that the remaining seeded species were offsetting local plant species that would otherwise occupy the site. Regardless of species seeded, total cover values converged at 4–5 years post-wildfire, suggesting that ecosystems may only support a threshold level of plant cover (Connell and Slatyer, 1977; Noble and Slatyer, 1977) and post-wildfire seeding actually suppresses the establishment of local species after fires (Anderson and Brooks, 1975; Schoennagel and Waller, 1999; Sexton, 1998; Barclay et al., 2004; Keeley, 2004). Fire restoration research in eastern Spain suggests that cover in the seeded plots and in the controls may reach similar values even more quickly under optimal conditions (Bautista et al., 1997; Vallejo and Alloza, 1998), in which case seeding may not provide any additional benefit to post-wildfire landscapes.

Data from this review cannot assess the differences in vegetation composition between seeded and non-seeded sites. Longer term monitoring results (i.e. >5 years) are needed to assess lasting impacts of seeded species. Assessment of soil seed banks is also needed to determine whether seed of non-persistent seeded species can remain viable within the seed bank (Griffin, 1982).

Seeding can negatively affect native plant communities by reducing native species richness through seeded species dominance in the first and/or second year after fire. Authors defined seeded species dominance in terms of high cover, biomass, density, and/or frequency. Seven of nine studies assessing seeding treat-

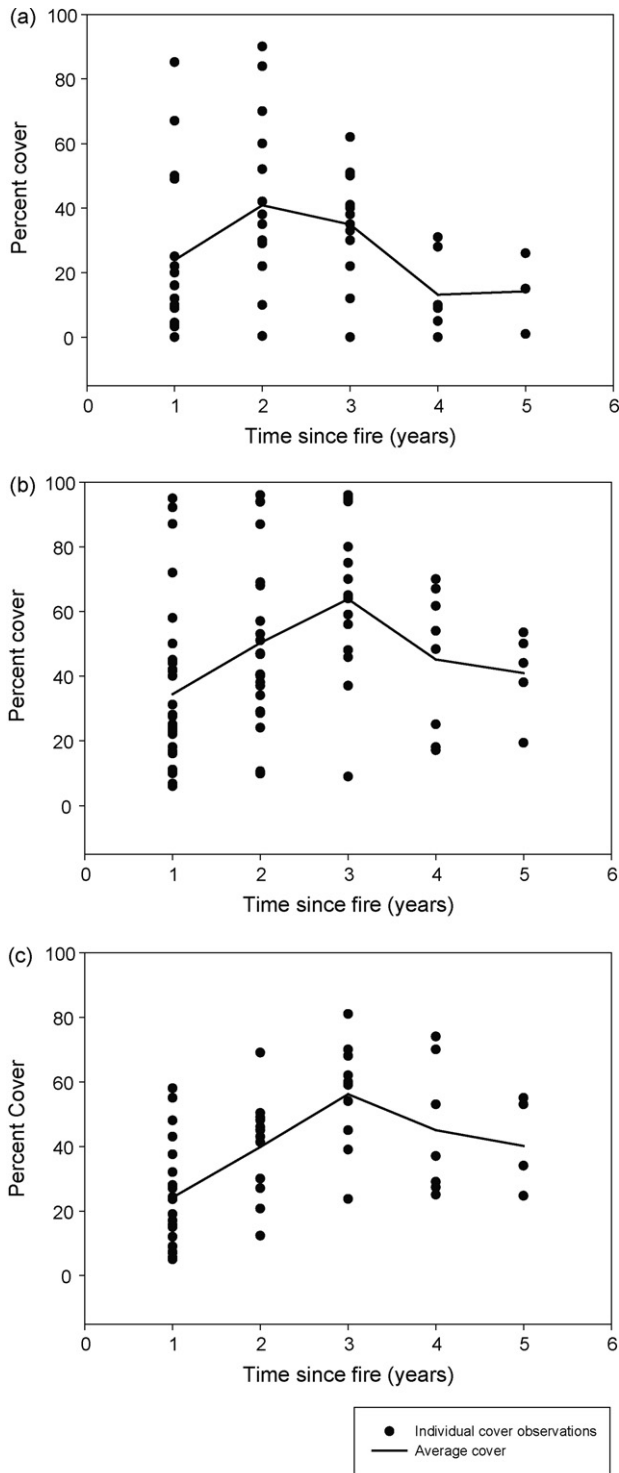


Fig. 5. Average (a) seeded cover (seeded species only), (b) total cover (seeded + unseeded species), and (c) control cover (unseeded) versus time since fire (data from 57 sites contained in 15 studies assessing post-wildfire seeding treatment performance in forested ecosystems in the western U.S.).

ment effects on native species richness reported reduced native species richness, while the remaining two showed no difference in native species richness on seeded versus unseeded controls. Six studies reporting decreased native species richness were of highest and high quality evidence, two-thirds of which were published since 2000. Reduced native species richness is often a function of high dominance by seeded species (Conard et al., 1991;

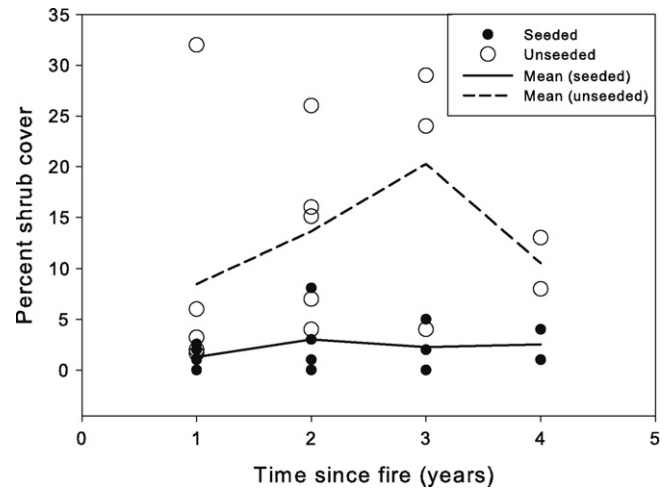


Fig. 6. Average percent shrub cover in seeded and unseeded sites versus time since fire in years (data from 16 sites contained in 14 studies assessing post-wildfire seeding effects of seeded grasses on shrub establishment in forested ecosystems in the western U.S.).

Amaranthus et al., 1993; Sexton, 1998; Schoennagel and Waller, 1999; Keeley, 2004). In five cases, studies reported high seeded species dominance coincident with reduced native species richness. For example, Barclay et al. (2004) noted a reduction in native forb richness in the second year following fire in north-central New Mexico coincident with low seeded annual ryegrass cover. However, total cover was also reported to be low; thus, the relative abundance of seeded ryegrass compared to other species may have remained high. The authors suggested that dominant ryegrass cover may have led to the initial suppression of native species, leading to a subsequent lack of reproduction of native forbs. In the two studies reporting no difference in native species richness between seeded and unseeded plots, one showed minimal cover of seeded annual species in both the first and second year post-wildfire in the Southwest (Stella, 2009). The other found that although seeded non-native annual and perennial grass and legume species had high cover and frequency in seeded plots in the eastern Cascades, a native plant, pinegrass (*Calamagrostis rubescens* Buckley), also dominated the site, which may have counteracted any effects of seeded species abundance (Schoennagel, 1997).

A number of studies examined competitive effects of seeded grasses on woody plant establishment. The potential for seeded grasses to compete with woody plant species can be viewed as positive or negative depending on the ecosystem or site being rehabilitated. Of 14 papers investigating post-wildfire seeding effects on tree seedling growth and shrub cover, the majority (11 papers) found seeding to negatively affect woody plant establishment. All studies seeded only grasses in treated plots. Two of the four studies providing highest or high quality evidence found that seeding negatively affected tree seedling and/or shrub growth and survival. One paper reported seeding had no effect on the growth and survival of woody species, while the other showed seeding improved establishment. Of five studies quantifying shrub cover in sites seeded with non-native species versus unseeded controls (16 sites), shrub cover in unseeded plots was almost always higher than in seeded plots (Fig. 6).

Soil moisture may influence establishment and survival of trees and shrubs; soil moisture can be depleted more rapidly on seeded sites yielding high plant production, thus limiting water availability to woody plant species (Elliott and White, 1987). For example, Amaranthus et al. (1993) found that seeded annual ryegrass suppressed first-year sugar pine (*Pinus lambertiana* Douglas) seedling growth in southwestern Oregon by lowering soil mois-

ture availability and reducing root-tip and mycorrhiza formation. Six other studies found reduced conifer seedlings and/or shrub growth and survival on sites dominated by seeded annual non-native species (Griffin, 1982; Conard et al., 1991; Schoennagel and Waller, 1999; Barclay et al., 2004; Keeley, 2004; Kruse et al., 2004). In contrast, Sexton (1998) noted no difference in ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws.) and antelope bitterbrush (*Purshia tridentata* (Pursh) DC.) seedling establishment on plots seeded with annual ryegrass versus controls in south-central Oregon; he found similar soil moisture levels on seeded and control plots, suggesting the seeded grass did not usurp soil moisture. These results suggest that seeding non-native annual species may negatively affect woody plant seedlings through competition for available resources (specifically soil moisture), space, and light during the first 2 years after fire (Beyers, 2004) and that important consideration must be given to the types of species seeded.

In summary, the effects of seeding on native plant recovery are strongly influenced by which species are seeded, post-wildfire precipitation intensity, fire severity, and time since fire (Schoennagel and Waller, 1999; Barclay et al., 2004; Hunter and Omi, 2006; Robichaud and Elliot, 2006; Wagenbrenner et al., 2006; Peterson et al., 2007; Rough, 2007). Variation in these factors, individually or in combination, will ultimately determine the direction and magnitude of any impacts seeded species may have.

4. Conclusions

Among U.S. natural resource agencies, seeding continues to be used as a common post-wildfire rehabilitation measure, although the use and success of this treatment continues to be debated. Our systematic review provides evidence that seeding to reduce post-wildfire soil erosion and non-native species invasions has uncertain results.

Indication that seeding is often ineffective in meeting post-wildfire management objectives related to soil erosion has strengthened as improved sampling designs produced more statistically robust data. Due to a shortage of long-term studies (beyond 2 years post-wildfire), assessment of multi-year effectiveness could not be quantified, although the studies available showed a trend of soil stabilization in both seeded and unseeded sites by year 5. In addition, there appears to be only a weak relationship between measurements of vegetative cover and reduction of erosion. Erosion may be better reduced by mulching, but care must be taken to ensure that mulch is free of non-native seed. Future research efforts should focus on developing more appropriate measures to evaluate seeding success as well as quantifying effectiveness and effects of mulching.

Evidence of seeding effectiveness for non-native species invasions is contradictory. Successful exclusion of non-natives often resulted when seeded species, specifically annual non-native species, produced high cover. Conversely, these same studies showed high seeded species cover displaced native species. Thus, both effective and ineffective treatments have the ability to suppress native species recovery. Any lasting effects that seeded non-native annuals may have on native plant communities can only be addressed by continued monitoring. Moreover, studies assessing the use of native species to combat non-native species invasions in burned areas are almost non-existent. Taking a closer look at the use of native species to reduce non-natives would be valuable.

Studies showed that post-wildfire seeding often decreases native species cover in the short-term, but we found little information addressing the effects of seeding on long-term post-wildfire vegetation recovery. Although seeding with non-local genotypes of native plants has been identified as a concern, we found no studies that addressed genetic consequences of post-wildfire native seed-

ing. Given ongoing debates about seeding, additional research on the long-term effects of seeding with both native and non-native species on natural vegetation recovery and the genetic integrity of native populations is essential.

Acknowledgments

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Appendix A. Evidence-based review references (with quality of evidence ratings)

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Amaranthus, M.P., Trappe, J.M., Perry, D.A., 1993. Soil moisture, native revegetation, and *Pinus lambertiana* seedling survival, growth, and mycorrhiza formation following wildfire and grass seeding. *Restor. Ecol.* 1, 188–195. (**Quality of Evidence Rating: Highest**)

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Becker, R., 2001. Effective aerial reseeding methods: market search report. USDA Forest Service 5100 – Fire Management, 0151 1204 – San Dimas Technology & Development Center, San Dimas, CA. (**Quality of Evidence Rating: Lowest**)

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Beyers, J.L., 2004. Post-fire seeding for erosion control: effectiveness and impacts on native plant communities. *Conserv. Biol.* 18, 947–956. (**Quality of Evidence Rating: High**)

Bruggink, J., 2007. Long term ecological changes with post-fire emergency seeding. In: Furniss, M., Clifton, C., Ronnenberg, K. (Eds.), *Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference*, San Diego, CA, 18–22 October 2004. Gen. Tech. Rep. PNW-GTR-689. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, pp. 20–26. (**Quality of Evidence Rating: Low**)

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