RESEARCH REPORT

Broadcast Seeding as a Potential Tool to Reestablish Native Species in Degraded Dry Forest Ecosystems in Hawaii

Samuel Brooks, Susan Cordell and Lyman Perry

ABSTRACT

Hawaiian dry forests currently occupy a small fraction of their former range, and worldwide tropical dry forests are one of the most human-altered systems. Many small-scale projects have been successful in restoring native dry forests in abandoned pastures and degraded woodlands by outplanting after invasive species removal, but this is a costly approach. In this project, we tested forest restoration techniques involving broadcasting seeds pretreated to enhance germination and applying herbicide to reduce non-native grass competition. We compared three treatments: broadcast seeding, herbicide, and broadcast seeding combined with herbicide. After two years our study results suggest that broadcast seeding and the favorable microclimate created by eliminating invasive grasses through herbicide application may increase native seed germination and survival and promote higher species diversity.

Keywords: broadcast seeding, dry forest, Hawaii, *Pennisetum clandestinum*, restoration

Hawaii's dry forests have been reduced by 90%, mostly over the past two centuries; the remaining fragments of forest are heavily degraded owing to invasive plant introductions, grazing, fire, logging, conversion to pasture, and other human activities (Bruegmann 1996, Cabin et al. 2000). One of the greatest dangers to dry forest is non-native pasture grasses, which are aggressive and effective competitors for light, water, and nutrients and thus have substantial ecosystem-level effects (D'Antonio and Vitousek 1992, Litton et al. 2006, Williams and Baruch 2000). In Hawaii, non-native grasses such as fountain grass (*Pennisetum setaceum*) and kikuyu grass (*P. clandestinum*) regrow quickly after fire and dominate large areas. Over a 40-year period (1954–1994), invasive grassland area increased by 237% in an area of 1,766 ha within the North Kona, Pu'u Wa'awa'a Ranch (Blackmore and Vitousek 2000). Competition with introduced pasture grasses is one main factor impeding native seedling survival in some tropical forest systems (Holl et al. 2000). Grass invasions increase fire frequency and intensity such that non-fire-adapted native vegetation survival decreases and fire-adapted grass distributions and biomass increase (D'Antonio and Vitousek 1992, Hughes et al. 1991).

The establishment of tree and shrub cover should suppress light-requiring non-native C_4 grass species while facilitating the establishment of other woody species and may be the first step toward reestablishing native forests in pastures (Holl 1999, Holl et al. 2000). Fast-growing native shrubs or vines can shade out pasture grasses and successfully compete for water and nutrients (Cabin et al. 2002). In remote island ecosystems such as Hawaii, however, seed dispersal is a major constraint to the development of native woodlands (Denslow et al. 2006, Holl et al. 2000). Low densities of adult woody plants in converted landscapes result in a reduced or absent native seed bank. We predicted that broadcast seeding would jumpstart reestablishment of native plants that have been displaced by over a century of ungulate grazing.

Small-scale native forest recovery projects have been effective in abandoned pastures and degraded woodlands by planting seedlings and reducing grass competition via grass removal (Cabin et al. 2002). This may be costly, however, especially on a large scale (Holl et al. 2000, Cabin et al. 2002). While ungulate exclusion, grass removal, direct seeding (Cabin et al. 1999), outplanting, and other techniques have been successfully used in Hawaiian dry forest fragments, they have not been integrated to treat relatively large areas of degraded forest. Cabin and others (2002) recommended the seeding of fast-growing native shrub and vine species as a more practical technique. Broadcast seeding, when combined with other restoration

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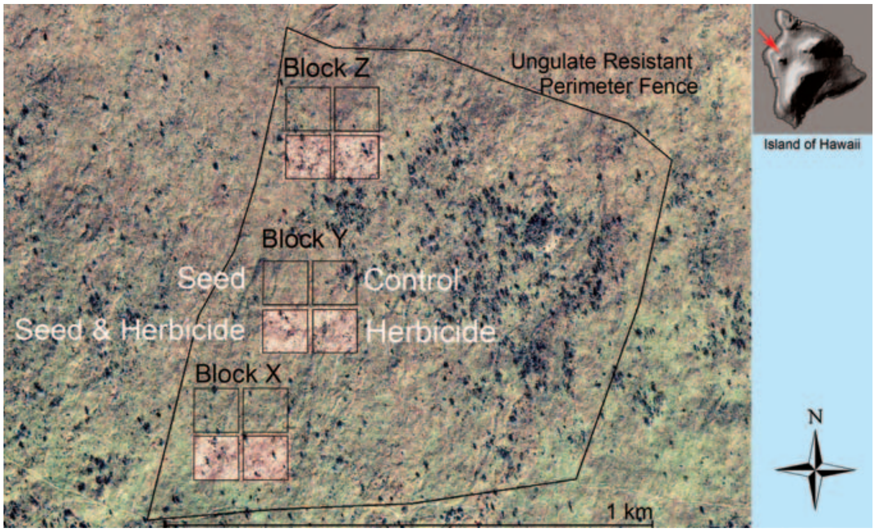

Figure 1. Experiment layout (1 ha treatment combination plots with 5 m buffer zones) for dry forest seeding and herbicide experiment. Blocks X, Y, and Z have the same treatment design. Image is IKONOS pan-enhanced pseudo-multispectral with 1 m resolution.

strategies (Hayes 2001), is an efficient way to restore large, inaccessible areas that would be costly to plant (Arnup et al. 1988) and has been an effective restoration technique in continental grassland systems (Wilson et al. 2004). Also, timing of seeding during wetter periods may do away with the need for additional watering. In this project we attempted larger-scale forest restoration using pretreated seeds to enhance germination and large-scale herbicide application to reduce non-native grass competition. We examined the effects of broadcast seeding alone, herbicide alone, and their combination on seed germination and survival in a dry forest environment.

Methods and Materials

Study Site

The study was established in a transitional degraded montane dry forest known as Waihou, located in Puuwaawaa on the western side of the island of Hawaii. Waihou Forest once connected the moist montane mesic and lowland dry forests. Early botanist Joseph Rock claimed that Puuwaawaa was the most botanically rich area in the whole Territory of Hawaii (Rock 1913). Ranching was first recorded at Puuwaawaa in the 1880s and continued for most of the 20th century. Ungulates destructively browse native tree seedlings and saplings in Hawaiian dry forests (Scowcroft 1983). Four tree species within Waihou are listed as endangered by the U.S. Fish and Wildlife Service (Hawaiian common names provided): aiea (*Nothocestrum breviflorum*), 100 wild individuals; hau kuahiwi (*Hibiscadelphus hualalaiensis*), cultivated, extinct in the wild; ae (*Zanthoxylum dipetalum* var. *tomentosum*), fewer than 15 known wild individuals found only in North Kona; and leechleaf delissea (*Delissea undulata*), cultivated and presumed extinct in the wild.

The Waihou preserve is an 81 ha enclosure surrounded by an ungulate-resistant fence constructed in 2004 (Figure 1). Waihou is characterized by open pasture, marked with standing skeletons of dead trees, and some remnant forest. The open canopy forest is an ohia/mamane (*Metrosideros polymorpha*/*Sophora chrysophylla*) community with an understory composed primarily of kikuyu grass, an aggressive non-native that forms a mat-like structure that smothers other plants and allows very few native seedlings to establish (Wagner et al. 1999). Other invasive groundcover species include fountain grass, fireweed (*Senecio madagascariensis*), hamakua pamakani (*Ageratina riparia*), German ivy (*Delairea odorata*), kolomona (*Senna pendula*) and banana poka (*Passiflora mollissima*). Natural regeneration of native koa (*Acacia koa*) and mamane has occurred since the parcel was enclosed in 2004.

The reserve is located at an elevation of 1,040 to 1,150 m on the slope of Hualalai Volcano and is situated on a 1,500–3,000 year-old *aa* lava flow from Hualalai volcano (Moore and Clague 1992). The area is gradually sloped with a north-facing aspect. Rainfall recorded in 2005 was 660 mm, which was higher than the mean yearly rainfall for the area of 600 mm (Giambelluca et al. 1986).

Experimental Design

Gridding of the enclosure and an initial ground vegetation survey were conducted in spring of 2005 using a systematic random sampling approach. Transect lines were put in place at 100 m intervals, with the position of the first transect being selected randomly. Beginning again with a randomly selected starting point on these transect lines, we established 169 permanent 1 m^2 plots at 50 m intervals to measure species composition and plant height throughout the enclosure; this provided an initial analysis of ground cover and height.

We located experimental plots by selecting replicates in areas with similar tree density, ground cover, and terrain (Figure 1). The experiment was constructed as a complete split-block design with grass control on the row (herbicide treatment or no treatment) and seeding on the column (seeding application or no seeding application). The treatment combination plot size was 1 ha, and with three replicate blocks, the entire experiment totaled 12 ha, a relatively large area compared to past restoration attempts in Hawaii. Each treatment combination plot was 100 m × 100 m with a 5 m buffer zone around the perimeter to reduce edge effect. All trees within the experimental plots were documented.

Table 1. Broadcast seed mix used in dry forest seeding and herbicide experiment, listing Hawaiian and scientific names. Seed origins are all located on the west side of the Island of Hawaii.

Species	Collection location	Seeding rate per hectare
Mamane *Sophora chrysophylla*	Puuwaawaa	936
Kului *Nototrichium sandwicense*	Kaupulehu	2,250
Aweoweo *Chenopodium oahuense*	Kaupulehu	7,200
Aalii *Dodonaea viscosa*	Puuwaawaa	936
Awikiwiki *Canavalia hawaiiensis*	Kaupulehu	936
Kolomona *Senna gaudichaudii*	Kaupulehu	936
Ulei *Osteomeles anthyllidifolia*	Puuwaawaa	1,872
Ilima *Sida fallax*	Puuwaawaa	3,744

We applied glyphosate (Roundup Pro) at 4% a.i. concentration manually with Solo backpack sprayers to the herbicide treatment plots from June to November 2005 at a rate of 5.9 kg/ha. In the first two months, herbicide was applied once to the entire area. In the four later months, we spot sprayed to suppress new grass seedling growth. The timing of herbicide spraying was designed to reduce grass cover during the dry season (June–September).

We broadcast seeds at 17,970 seeds per hectare on November 29, 2005, to coincide with the beginning of the wet season at Puuwaawaa. We took advantage of the short window of time after grass removal and before the winter rains. Previous studies have shown that grass recovery following disturbance is slow (Nonner 2005). We pretreated seeds following the protocol of Lilleeng-Rosenberger (2005) because germination rates for many native species are known to be slow (A. Yoshinaga, Center for Conservation Research and Training, pers. comm.). We selected eight fast-growing species of native shrubs and vines (Table 1) that have been successful in previous studies (Cabin et al. 2002). Seeds were collected March through August 2005 within a 16 km radius of Waihou to ensure local adaptation of selected species.

We broadcast evenly throughout each selected plot in a single day. This was accomplished with the help of 50 volunteers. We subdivided the 100 m × 100 m block into 8 equally sized smaller blocks (20 m × 50 m) and within each subblock, two volunteers distributed the seeds uniformly from one end to the other moving in a zigzag pattern. Each subblock received the same number and proportion of seed species.

Data Collection and Analysis

Prior to treatment manipulation, all live trees greater than 2 cm diameter at breast height (dbh) were mapped within the experiment blocks. The dbh of each stem was recorded to the nearest 0.01 cm on the uphill side of the tree. Understory plants were surveyed in 1 m² plots using Domin percent abundance estimates at 5 m intervals (Hill et al. 2005). Pretreatment photographs were taken in each of the experimental plots to document change over time. In addition, satellite imagery documented the effectiveness of the herbicide treatment, using a pan-enhanced pseudomultispectral 1 m resolution IKONOS image (Figure 1).

Seedling counts were conducted in December 2007 and January 2008, two years after herbiciding and seeding. We established nine 10 m diameter sampling plots per treatment hectare; three replication blocks resulted in 27 circular sampling plots per treatment combination, for a total of 108. Plots were established using systematic sampling at 30 m intervals. Native species were grouped according to height (seedlings < 1 m, saplings 1–2 m, and saplings > 2 m). We assumed that seedlings became established the two years after broadcast seeding. Saplings (≥ 1 m) were considered to have existed prior to treatment. A two-year return interval for sampling was chosen to allow for a better indication of seedling establishment and to aid in visually locating seedlings.

The data were analyzed using Minitab (vers. 15, State College PA) for ANOVA. Post hoc comparisons of treatment means with the control means were made using Dunnett tests.

Results

In the pretreatment tree survey, basal area was calculated from dbh. There was no significant difference in basal area between treatment blocks. The mean basal area for the blocks was 0.68 m²/ha.

A randomized blocking term within the split-plot design indicated no significant difference between blocks. In the posttreatment seedling survey there was an overall significant difference between treatments. Post hoc analysis indicated that seed germination and seedling survival were significantly higher in the combined broadcast seeding/herbicide plots than with seeding only, herbicide only, and control treatments ($p < 0.01$, Figure 2). Survival after 2 years was 3.4%. Neither the broadcast-seeding-only treatment nor the herbicide-only treatment produced a significant difference from the control (Figure 2). The dominant seedling was mamane, comprising 72% of all seedlings. In addition, we recorded koa 18%, aalii (*Dodonaea viscosa*) 2%, ohia 6%, and kolea (*Myrsine lanaiensis*) 2%. The combined herbicide/broadcast seeding treatment contained the highest diversity of native seedlings, with all five species represented. The herbicide-only and seed-only plots contained mamane and koa, whereas the control block contained only mamane seedlings. Five species were broadcast but not found in plots (Table 1). Native tree seedlings found in plots but not broadcast seeded included koa, ohia, and kolea.

The initial herbicide treatment suppressed grass regrowth for only four to

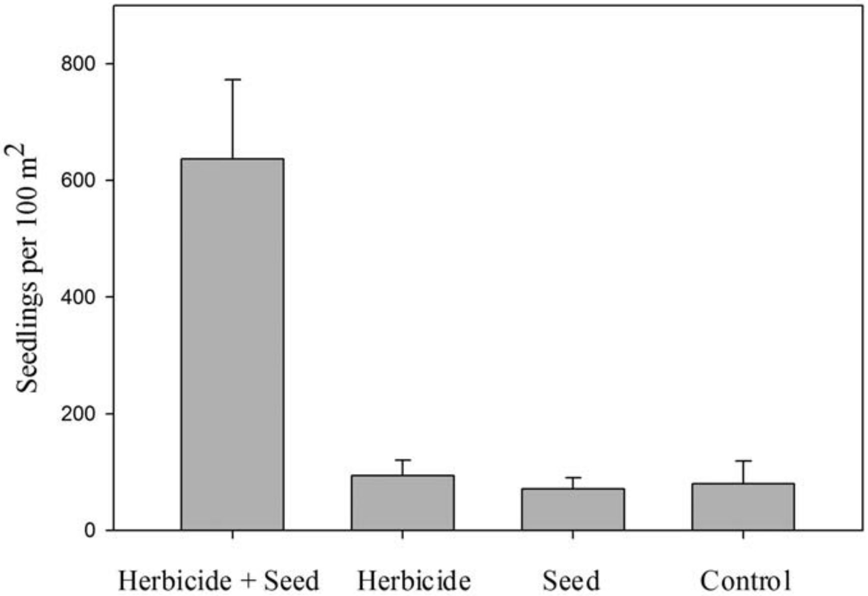

Figure 2. Mean seedling (± SE) counts by treatment combination two years after seeding and herbicide treatments in dry forest in Hawaii.

five weeks. This may be attributed to a wet summer for the area associated with a large non-native seed bank, which favored regrowth. Kolomona and banana poka were not effectively killed by the glyphosate application but were present in low numbers and were not the target invasive species. Over 90% of the ground cover within the enclosure was kikuyu grass. Fountain grass grew predominantly on rocky areas with less soil and covered approximately 5% of the area.

Discussion

The study results suggest that the combination of broadcast seeding and herbicide application may increase native seed germination and survival and promote higher species diversity in Hawaiian tropical dry forests. Some of the species found in the herbicide seed plots were not in the broadcast seeding mixture and likely regenerated naturally owing to the increase in suitable microsites resulting from the herbicide application. It is not surprising that neither the broadcast-seeding-only treatment nor the herbicide-only treatment resulted in significant survival differences from the control, because multiple techniques appear to be critical for effective restoration in dry forest systems (Cabin et al. 2002).

Only a small number of seedlings were observed in all the plots relative to the total amount of seed that was broadcast and, as indicated by control plot counts, some of these originated from the seed bank. Of the seeded species, ulei (*Osteomeles anthyllidifolia*) required the longest germination period, up to six months, and no representatives of this species were found in the plots. In contrast to the Cabin and colleagues (2002) finding of virtually no "natural" native species recruitment, this study observed several species. In fact, the species koa, with the second highest germination rate in the plots, was not seeded and must have been present in the seed bank or sprouted from existing root systems. This large-seeded legume with a thick seed coat likely forms a long-lived seed bank, up to 25 years (Judd 1920). Previous studies confirm that koa requires scarification and light for regeneration (Whitesell 1984); the herbicide allowed for greater light, and possibly the increase in foot traffic (50 volunteers) caused some scarification of seeds on the ground.

The low rate of seed survivorship is likely a result of our pretreatment approach. The soaked seeds were moist and soft, likely increasing predation pressure. Non-native rodents depredate native fruits and seeds in Hawaiian dry forests (Chimera 2004), and we noted after seed dispersal that snails were depredating certain seeds, primarily the larger awikiwiki (*Canavalia hawaiiensis*) seeds. Another observed barrier to seed germination was the substantial amount of matted dead biomass of kikuyu grass that remained post–herbicide treatment, which likely prevented some seeds from reaching a suitable microenvironment for germination.

Past studies in the region indicate that up to three or four herbicide applications are necessary to effectively stop grass regrowth (Cordell et al. 2002, Denslow et al. 2006), although a study on Maui found that a single application of herbicide reduced kikuyu grass from 70% to less than 5% (Medeiros and vonAllen 2006). The rough terrain of the study area, primarily *aa* lava with furrows, collapsed lava tubes, and inclines, proved difficult to maneuver on foot with backpack sprayers. Water for mixing herbicide had to be transported by foot to the sites, a trip of up to 400 m. Aerial herbiciding was originally planned for this study but was not conducted owing to the presence of several endangered tree species. For large tracts of degraded land, aerial herbicide applications can be extremely cost-efficient, with cost per unit area as little as a tenth that of ground applications (Motooka et al. 2002).

In terms of the costs of the project, volunteers accomplished approximately half the labor (48%), providing 72 h/ha herbicide spraying, 13 h/ha seed preparation, and 8 h/ha broadcast seeding. Administering herbicide was the most time-consuming portion of the project (approximately 70% of total time). A full-time technician spent a total of 40 h/ha collecting native seeds and 60 h/ha spraying herbicide. The cost for herbicide was $250 per ha.

Our project had a seed survival rate of 3.4% after two years, comparable to the findings of Tenenbaum (1994), who reported a 3% survival rate for planted native tree species in a tropical dry forest in Costa Rica after three years. Another Hawaiian dry forest study observed an outplanting tree seedling survival rate of 34%, but that effort was more labor intensive, since the seedlings received supplemental watering for six months (Cordell et al. 2008). Comparing costs and results of planting seedlings verses broadcast seeding in this environment may be a needed direction for future research.

Recommendations

Recommendations for future broadcast seeding projects include disseminating larger quantities of seed and testing different seed pretreatments. In addition, the removal or partial removal of standing biomass following herbicide application will increase light, which koa and many other native plants require for germination (Whitesell 1984). Seeds could be placed in gaps in the dead biomass, which may serve as suitable microsites. Shading can significantly increase seedling survival (Cabin et al. 2002, McLaren and McDonald 2003), and the dead grass can also reduce the likelihood of non-native species encroachment. Cabin et al. (2002) noted that shading doubled the percent cover of native species.

In large-scale restoration efforts where individual planting is prohibitively costly and labor intensive, broadcast seeding in combination with herbicide application may be an effective way to restore native ecosystems and decrease the biomass and distribution of non-native, fire-adapted grasses. Results from this study may have a broad application in dry, tropical, grass-invaded ecosystems, and over time these efforts may aid in reversing the cycle of grass invasion and wildfire (Cordell et al. 2004). The ultimate goal is to transform these degraded and highly flammable, low-diversity, non-native-dominated grasslands to less flammable, native-dominated woodlands (D'Antonio and Vitousek 1992). Native forest rehabilitation and restoration may be the most cost-effective management approach to reduce fuel loads, fire danger, and fire impacts while also controlling invasive species establishment and spread.

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