POSITIVE AND NEGATIVE SIGNALS REGULATE GERMINATION IN THE POST-FIRE ANNUAL, NICOTIANA ATTENUATA

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Abstract. The litter of many plant species is known to inhibit germination, and this phenomenon is commonly interpreted as allelopathic inhibition of one species by another. However, an alternative interpretation is that seeds may be using environmental signals to inform the timing of their germination and thereby use dormancy as a mechanism of habitat choice. Nicotiana attenuata Torr. ex Wats. (Solanaceae) is typically found for less than three years after fire in the sagebrush, blackbrush, and pinyon–juniper forests of the Great Basin desert of North America. A dormant seed bank is established during this ephemeral post-fire period, and pyrolysis products of α-cellulose (containing only C, H, and O) in wood smoke are known to initiate germination in dormant seeds of this species. We demonstrated in a glasshouse experiment that germination into burned soils (as compared to unburned) results in a 12-fold increase in lifetime seed production, which reflects a minimum estimate of the fitness benefit of making accurate germination decisions. With seed bioassays, we examined the distribution of this smoke signal in the A1 soil layer at several burned areas in southwestern Utah, United States to determine whether the presence of this smoke-derived germination cue predicts the spatial and temporal occurrence of N. attenuata populations after fires. Although we found no evidence for the germination signal in areas that had not been burned for 30 yr, the occurrence of the germination signal did not perfectly coincide with the distribution of populations. We found evidence for its transport by wind and water into adjacent unburned areas (from 40 m to 1 km away from a burned site) and its persistence over time (for ≥7 yr), making this signal an unreliable indicator of the plant’s habitat. To resolve this discrepancy, we examined the effect of unburned A0 soil horizon on smoke-induced germination. The litter-containing A0 soil horizon (and aqueous extracts thereof), collected from underneath seven dominant species from later stages of post-fire succession, completely inhibited germination of both dormant and nondormant seeds, even in the presence of a smoke cue in excess of that required to elicit germination. The inhibitory effect was limited to the early stages of germination (48 h after exposure to smoke), and we confirmed these results with natural seed banks. We demonstrated that the A0 soil horizons and their aqueous extracts are not toxic to N. attenuata seeds or growing plants, and they have no effect on lifetime seed production. Moreover, they do not inhibit the germination of the nondormant, conspecific native tobacco, N. trigonophylla, which grows in the same area but is not associated with fire. Hence, these negative factors do not function in allelopathically mediated competitive interactions between N. attenuata and later successional species. We propose that the occurrence of N. attenuata populations after fires can be explained by the combined stimulatory effect of smoke-derived signals on the dormant seed bank and the inhibitory effect of signals from unburned litter, and that both signals are required for N. attenuata to identify its germination niche.

Key words: A0 and A1 soil horizons; allelopathy; fire; germination signals; litter-inhibited germination; Nicotiana attenuata; positive and negative control; seed banks; seed dormancy; smoke-induced germination.

INTRODUCTION

Dormancy functions to distribute organisms in time and, much like its spatial counterpart, dispersal, can be directed or random, allowing plants to synchronize growth with suitable environmental conditions (Bouwmeester and Karssen 1993). To cope with the lack of reliability of proximate signals, some species may have evolved “bet-hedging” strategies, whereby only a certain fraction of the dormant seed bank germinates under favorable conditions (Brown and Venable 1986, Philippi 1993b). The mechanisms used by seeds to terminate dormancy and initiate growth are expected to allow plants to select favorable habitats. Many seeds use cues as general as temperature, photoperiod, moisture, or seed age (Mirov 1936, Philippi 1993a), but germination signals can be much more habitat specific.
The most dramatic example of this specificity is Striga asiatica (Scrophulariaceae), a holoparasite with stringent requirements for host attachment (Chang and Lynn 1986). Germination is initiated by a root exudate from its host, a hydroquinone that is oxidized to an inactive form as it diffuses through the soil from the host and provides information to the seed about its distance from a suitable host (Lynn and Chang 1990).

The community of annual plants that flourish in post-fire environments contains many species that appear to synchronize their germination with fire-related cues (Keeley and Keeley 1989, Keeley 1991). For these species, the combination of open space, increased availability of resources, and temporary reduction in predators is highly favorable for seedling establishment (Evans 1976, Moreno and Oechel 1991, Simons 1991, Bond and van Wilgen 1996). Fire provides a number of factors that stimulate germination, such as heat, inorganic nutrients, unidentified compounds associated with blackened (charred) wood (Went et al. 1952, Stone and Juhren 1953, Quick and Quick 1961, Christensen 1966), and may blacken (charred) wood (Went et al. 1952, Stone 1958). Fire provides a number of factors that stimulate germination, such as heat, inorganic nutrients, unidentified compounds associated with blackened (charred) wood (Went et al. 1952, Stone and Juhren 1953, Quick and Quick 1961, Christensen 1966), and may blacken (charred) wood (Went et al. 1952, Stone 1958). Fire provides a number of factors that stimulate germination, such as heat, inorganic nutrients, unidentified compounds associated with blackened (charred) wood (Went et al. 1952, Stone and Juhren 1953, Quick and Quick 1961, Christensen 1966), and may blacken (charred) wood (Went et al. 1952, Stone 1958).

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Nicotiana attenuata Torr. ex Wats. (Solanaceae) is a tobacco native to the Great Basin desert of California, Nevada, Idaho, and Utah, United States (Goodspeed 1954, Wells 1959, Brotherson et al. 1980). It primarily occurs ephemerally (typically less than three growing seasons) after fire in sagebrush and pinyon–juniper ecosystems. Limited populations may occur persistently (for many growing seasons) in isolated washes and as a roadside weed after new construction in a previously undisturbed area (Wells 1959, Barney and Frischknecht 1974, Britton and Ralphs 1978, Young and Evans 1978, Wright et al. 1979, Konia and Everett 1982, Wright and Bailey 1982, Konia 1985, Baldwin and Ohmeiss 1993, Baldwin and Morse 1994, Baldwin et al. 1994; I. T. Baldwin, unpublished data). Close scrutiny (I. T. Baldwin, unpublished data) of a mature juniper habitat in southwestern Utah (site 5; Table 1) found no N. attenuata plants for eight consecutive years, and the nearest population was >8 km downslope from this site. A fire on 5 July 1994, originating from a lightning strike, burned 809.4 ha and killed all of the junipers, some of which were >150 yr old. In the growing season following the fire, N. attenuata was the dominant plant, with >10,000 individuals growing in this burned area. Because there are no known seed dispersers for this species, it is reasonable to infer that the dramatic post-fire response resulted from the germination of a long-lived dormant seed bank. Based on the age of the junipers, the seed bank may have been more than one century old. Because junipers are easily killed by fires and do not resprout from burned stumps (Wright et al. 1979), their age provides a method of determining the between-fire interval. In pinyon–juniper forests, this interval averages 10–30 yr (Wright et al. 1979), but can be as long as 115 yr (Konka 1985). The occurrence of plants in nature may be limited by either pre- or post-germination processes, however, post-germination regulation would not be compatible with the maintenance of a long-lived seed bank. We have established that dormant seeds of this species germinate, both in natural seed banks and in laboratory bioassays, in response to water-soluble factors in wood smoke (Bald-
win and Morse 1994, Baldwin et al. 1994). The germination cue(s) is produced after the combustion of pure cellulose (and, hence, is not dependent on the type of biomass burned), contains only C, H, and O (and, hence, is a different mechanism from the NO2-stimulated germination of E. penduliflora; Keeley and Fotheringham 1997), and is active in minute quantities of <1 pg/seed (Baldwin and Morse 1994, Baldwin et al. 1994; I. T. Baldwin and Z. P. Zhang, unpublished data).

Here, we ask whether the stimulation of dormant seed banks by the smoke-derived germination cue can account for the distribution of N. attenuata populations in nature. Because this smoke-derived germination cue is water soluble, the distribution of the cue after a fire may not coincide with the areas that were actually burned, for wind- and water-based transport could move the cue into adjacent unburned habitats. We collected soil samples to test three predictions regarding the distribution of the germination signal in nature. First, the amount of cue in the soils should be greatest immediately following a fire and should decrease rapidly, disappearing after a maximum of three years, reflecting the limited persistence of N. attenuata populations after a fire. Second, because the cue is water soluble (Baldwin et al. 1994), and persistent populations can be found in washes, we expect to find the cue leached downslope in washes leading away from recently burned areas. Third, when wind moves smoke into the unburned areas adjacent to a fire, it may cause seeds to germinate in these areas. However, as we do not find N. attenuata plants growing outside of the burned area, we predict that the concentration of the cue is not sufficient to initiate germination. The results did not fit many of our predictions and prompted us to consider other controls on the germination of these long-lived seed banks.

The inhibition of germination by plant-derived factors is more commonly reported than the stimulation of germination (Bewley and Black 1994), but the interpretation of their functional significance depends on the origin of these negative regulators of germination. When these negative factors are derived from the same taxa that produced the seeds, they are interpreted as examples of adaptive regulation of germination, e.g., leachable germination inhibitors found in seed coats functioning to gauge rainfall (Went 1949), or to signal successful dispersal from the parent plant (Evenari 1949, Harper 1977, Bewley and Black 1994). However, when these negative regulators arise from potential competitors in the plant community, their occurrence is commonly interpreted as competition mediated by allelopathic factors (Muller 1968, Rice 1984, Wardle et al. 1996). Allelopathic compounds can inhibit pre- and/or post-germination growth (Muller 1968, Rüdiger and Lohaus 1987), and xeric habitats may favor the accumulation of these allelochemicals due to their low rates of leaching and reduced soil microflora activity (Friedman 1987). Allelopathy has long been invoked as a mechanism explaining the dramatic post-fire flush of annuals, because fire may destroy allelopathic compounds that inhibit germination (McPherson and Muller 1969, Chou and Muller 1972, Chou 1973, Christensen and Muller 1975b, Christensen 1977), but the evidence for this explanation is thought to be weak (Keeley and Keeley 1989). For some species, therefore, fire may provide signals that activate the germination process and remove allelopathic compounds, suggesting that synchronized growth within the post-fire environment involves both positive and negative controls over germination.

We report evidence for the existence of water-soluble factors in the A0 horizons collected under seven species of dominant vegetation in the habitat of N. attenuata. These factors dramatically inhibit the initiation of germination of N. attenuata seeds, but have no deleterious effects on subsequent growth or reproductive performance. Moreover, these negative regulators of germination do not inhibit the germination of another native species of tobacco that occurs in the same area as N. attenuata, but is neither dormant nor associated with fires (Wells 1959). Thus, these inhibitors of germination are not the type envisioned by many researchers studying allelopathic interactions in fire-prone ecosystems, namely that of chemical suppression of one species growth by another. Rather, the inhibitors provide information and are used as chemical cues to time the germination of dormant seeds into appropriate habitats. Nicotiana attenuata clearly requires both positive and negative germination cues to accurately locate its germination niche. We propose that chemical “eavesdropping” by dormant seeds on products from established plants may be a better explanation of the frequently observed phenomenon of germination inhibition by the litter of many plant species.

**Materials and Methods**

**Site descriptions.**—Ten sites were sampled from April to July 1996 (Table 1). Data on fire dates and areas burned were from Bureau of Land Management (BLM) records at Cedar City, Utah. For the two oldest burns, fire dates were estimated from conversations with retired, local firefighters and from the age of trees (determined by coring and counting rings) that had grown since the fires. This cold desert is characterized by winter precipitation, with 42% of the annual total occurring from January through March, and only 12% from May through July. Annual precipitation at the Gunlock Powerhouse, Gunlock, Utah (T40S R17W; section 28), as recorded by the National Climatic data center, Asheville, North Carolina, averaged 36.66 ± 4.33 cm per year (mean ± 1 se) from 1985 to 1995.

**Soil collection.**—The A1 soil horizon is poorly developed in this arid climate and, at unburned sites, lies below a thick, litter-containing A0 horizon. Soil from the A1 horizon was sieved through wide- and fine-mesh sieves (U.S. Standard Sieve Series; No. 4: 4.75-mm
opening, No. 18: 1.0-mm opening, respectively; W. S. Tyler Company, Cleveland, Ohio, USA) and was stored in plastic bags for germination cue extraction and bioassays. All samples were collected adjacent to burned juniper stumps to control for the effects that different vegetation types may have on the surrounding soil. To determine the cue content in burns of different ages (Table 1), we sampled locations where ash or charcoal was still discernible and collected control samples in adjacent unburned areas, on separate slopes with the same vegetation history (except for the two oldest burned areas, sites 9 and 10, for which we could not determine the fires’ distribution). To determine how the germination cue is distributed within a burned area, we collected five samples at site 3 along a 20-m transect leading away from a burned juniper stump in the center of the burn. The A₀ soil horizons were also collected from two washes, leading ~1 km downslope from sites 4 (16 samples) and 5 (19 samples). Two upwind (20-m, 10 samples each) and one downwind (40-m, six samples) transects of samples were established from the edge of a 1-wk-old burn (site 1) into the adjoining unburned habitat. Prevailing wind directions at the time of the fire were obtained from the firefighters who helped to extinguish the fire. All samples were collected from April to July 1996.

**A₀ collection.**—The litter-containing A₀ horizon underneath the following species was collected from the unburned area adjacent to site 4: mormon tea (Ephedra sp.), blackbrush (Coleogyne ramosissima Torr.), bitterbrush (Purshia tridentata (Pursh) DC), big sage (Salvia sp.), holly oak (Quercus sp.), and pinyon pine (Pinus monophylla (Torr. and Frem.)). The A₀ horizon underneath juniper (Juniperus osteosperma (Torr.) Little) was collected in unburned areas adjacent to site 5. Juniper berries were removed from this collection. All samples were stored in large plastic bags at room temperature.

**A₀ and A₁ extracts.**—Soil horizons were ground in a Wiley Mill (Thomas Scientific, Swedesboro, New Jersey, USA) to standardize texture and grain size (850-µm mesh). Equal volumes (10 cm³) of the soil and hot distilled water were combined in a 25-mL glass scintillation vial and agitated on a shaking table for 8–12 h. To avoid inhibiting germination by the lack of nutrients, 1 mM KNO₃ was used instead of distilled water. In one experiment, the sterile sand was replaced with burned A₀ soil horizon. The same volume of soil was used, and 20 seeds were placed on top of the soil, which was then saturated with distilled water. To determine if the inhibitory effect of the A₀ horizon from under juniper (JA₀) on seed germination required direct contact with the horizon (perhaps due to unfavorable germination microsites), or if there is a leachable inhibitory component, 0.5 cm³ of intact or ground JA₀ was placed above and below the sand layer in the bioassay chamber containing seeds that had been previously exposed to liquid smoke. In this experiment, seeds were either in direct contact with JA₀ or were separated by a layer of sand. In another experiment, ground JA₀ was placed in increasing volumes below a layer of burned A₁ horizon on which seeds were placed, to examine the quantitative interaction between inhibitory cues leached from the A₀ horizon and stimulatory cues leached from burned A₁ horizon. Cups contained 2 cm³ of burned A₁ horizon collected at site 5, placed on top of 0–3 cm³ of ground JA₀, increasing in five increments. Twenty seeds were placed on top of the A₁ horizon and distilled water was added to saturate the horizons.

To determine when positive and negative germination signals influence the germination process, we moved seeds from bioassay containers with smoke extracts to containers with A₀ horizon extracts after different lengths of time. Under our bioassay conditions, radicles emerge from seeds beginning 3 d after expo-
sure to smoke extracts (Day 0). To determine when the negative cue (−) can inhibit radicle emergence, seeds were exposed to 1:300 liquid smoke on Day 0, and were transferred to new containers with extracts made from the A<sub>0</sub> horizon under unburned juniper trees (JA<sub>0</sub>Ex) separately on Days 1–6 (+ to − transfer; see Fig. 6A). To determine when the positive cue (+) can initiate radicle emergence after seeds have been exposed to the negative cue, seeds were exposed to JA<sub>0</sub>Ex on Day 0 and were transferred to new containers with 1:300 liquid smoke separately on Days 1–6 (− to + transfer; see Fig. 6B). Three replicate seed cups were used for each treatment and transfer day. Hence, we used 51 germination bioassays for this experiment (21 + to − transfer; 21 − to + transfer; six smoke and JA<sub>0</sub>Ex controls; and three water controls). Because most of the seeds in the − to + transfer treatment had not germinated 9 d after their transfer to smoke extracts, we treated these seeds with a 5% hypochlorite solution for 2 min to determine whether these nongerminating seeds were still viable (Baldwin et al. 1994). Bleached seeds were examined for radicle development for 19 additional days.

**Seed bank experiment.**—To examine the interaction of + and − germination signals under more natural conditions, we constructed 86 replicate seed banks, treated them with different combinations of smoke and JA<sub>0</sub>Ex, and monitored seed germination for 24 d, the approximate length of time each spring during which seeds germinate from natural seed banks in Utah (C. A. Preston and I. T. Baldwin, unpublished data). Seed banks consisted of soil collected from an unburned area at site 2, enriched with seed dehisced from mature plants growing at site 3 and, hence, contained both dormant and nondormant seeds. The use of seed banks with both dormant and nondormant seeds allowed us to determine whether JA<sub>0</sub>Ex also inhibited the germination of nondormant seeds. Both soil and seed were collected in July 1996. Two centimeters of the seed-enriched soil were placed on top of 7.5-cm pots containing sterile sand. Seed banks were randomly assigned to the following treatments: (1) a 1:100 dilution of liquid smoke, (2) JA<sub>0</sub>Ex, (3) a 1:1 mixture of 1:50 liquid smoke and JA<sub>0</sub>Ex, (4) distilled water, or (5) 100 liquid smoke applied at Day 0 and JA<sub>0</sub>Ex applied on Day 2. All seed banks were retreated every 10 d (treatment 5 received only JA<sub>0</sub>Ex). All treatment volumes were 20 mL, which for the JA<sub>0</sub>Ex treatment was equivalent to a 0.3 cm thick juniper litter (A<sub>0</sub>) layer. Seed banks were placed under a sodium vapor light delivering a minimum PAR level of 300 mmol·m<sup>−2</sup>·s<sup>−1</sup> at the soil surface, and their positions on the bench were rotated every 5 d. Seed banks were kept moist by bottom-watering into individual 8.5-cm saucers with distilled water. The number of seedlings germinating was counted every 4–6 d and seedlings were removed.

**Effects of JA<sub>0</sub>Ex on plant growth.**—Having established that JA<sub>0</sub>Ex dramatically inhibits germination, we sought to determine if JA<sub>0</sub>Ex is allelopathic to *N. attenuata*, inhibiting its vegetative and reproductive growth. Chiapuiso et al. (1997), in their recent review of bioassays in allelopathic research, concluded that seed germination bioassays were inferior to growth bioassays in predicting allelopathic behavior in the field. We assigned 20-d-old seedlings to the following four treatments, with eight replicates each: (1) unburned A<sub>1</sub> horizon, (2) burned A<sub>1</sub> horizon, (3) burned A<sub>0</sub> horizon with a 1-cm layer of ground JA<sub>0</sub> on the soil surface, and (4) burned A<sub>1</sub> horizon watered with 30 mL JA<sub>0</sub>Ex, equivalent to a 0.3 cm thick A<sub>0</sub> horizon. We filled 1-L pots, one-third full with sterile sand and two-thirds full with either burned or unburned soil collected from site 2 (Table 1). Pots on the glasshouse bench were rotated every other day. Pots in treatments 3 and 4 were top-watered with 30 mL of distilled water or JA<sub>0</sub>Ex, respectively, every other day. To keep the soil moist, pots were bottom-watered with distilled water when necessary. The JA<sub>0</sub>Ex was prepared in larger quantities than in the seed germination experiments (100 cm<sup>3</sup> of ground A<sub>0</sub> horizon from under juniper in 100 mL of distilled water), and was refrigerated until use. Plants were grown until senescence to determine lifetime seed production. Numbers of mature capsules were counted and two capsules were collected from branch positions 2–8, which have uniform capsule sizes (Baldwin et al. 1997), to determine estimates of the average seed mass per capsule and mass per seed for each plant. Lifetime seed production was estimated as the product of capsule number and average seed mass per capsule divided by the average mass per seed.

**Germination effects of JA<sub>0</sub>Ex on a nondormant tobacco species.**—To determine if the inhibitory effect of JA<sub>0</sub>Ex could be extended to other species growing in the same area, we exposed seeds of a nondormant tobacco species, *Nicotiana trigonophylla*, as well as seeds of the dormant tobacco species, *N. attenuata*, to undiluted JA<sub>0</sub>Ex. *Nicotiana trigonophylla* is commonly found in desert habitats of southern California and northern Mexico (Goodspeed 1954), but occurs sporadically in washes in Utah and Arizona. It is not associated with the post-fire environment (Wells 1959). Seeds originated from a single plant collection in 1987 in southwestern Utah (T41S R17W; section 29), and were propagated in the greenhouse for one generation of selfing. Germination bioassays were performed as previously described, with the exception that JA<sub>0</sub>Ex was produced using 1 mM KNO<sub>3</sub> instead of distilled water, and control replicates received only 1 mM KNO<sub>3</sub>. The use of KNO<sub>3</sub> prevents reduced germination responses that can be attributed to a lack of nutrients and not the presence of JA<sub>0</sub>Ex.

**Statistical analysis.**—The percentage of all seeds germinating in each bioassay container at each observation was arcsine-transformed for normality. Factorial ANOVAs on the transformed percentages were used to analyze main effects. Post hoc tests were performed.
Fig. 1. Mean (+1 se) differences in percentage germination of *Nicotiana attenuata* seeds treated with A₁ soil extracts vs. controls (seeds treated with water) 9 d after initial treatment in seed cup bioassays; asterisks indicate significant differences (see Results: Germination potential of A₁ horizon extracts for P levels). Each treatment and control had three replicate bioassays, each with 20 *N. attenuata* seeds. Extracts were prepared from soils collected at different distances: (A) from a burned juniper stump within the burned area of site 3; (B) downslope in a wash from site 4; (C) downslope in a wash from site 5; (D) and (E) along two upwind transects; and (F) along one downwind transect leading from burned juniper stumps at the edge of the burned area into adjacent unburned areas of site 1. Separate controls were performed for each experiment and had germination values of 6.7–16.7%. See Table 1 for site descriptions. Heavy bars along the x-axis depict the location of the burned area, and numbers describe the distance from the nearest burned juniper stump within the burned area.

with the Bonferroni adjustments of significance levels to compare individual treatments. Seed capsule number, seed mass per capsule, and mass per seed were analyzed with one-way ANOVAs. Analyses were performed with the STATVIEW 4.5 statistical package (Abacus Concepts, Berkeley, California, USA).

**Results**

**Germination potential of A₁ horizon extracts.**—Figures 1A–F and 2 depict the mean differences in percentage germination between seeds treated with A₁ soil horizon extracts and water-treated seeds. In all experiments, some extracts resulted in 100% germination,
but the background germination of water-treated seeds reduced the differences in mean germination responses to values <100%. All statistical analyses were performed on the arcsine-transformed germination percentage from each bioassay, and not on the difference data presented in Figs. 1A–F and 2.

All samples collected from within a 1-yr-old burned area showed significantly increased germination above water controls (Fig. 1A; $F_{5,12} = 10.33, P < 0.0001$). The two samples nearest to the burned juniper stump elicited significantly greater germination responses than did $A_1$ soil horizon samples collected at greater distances (all $P < 0.0001$). We conclude that the germination potential of $A_1$ horizon extracts can vary within a burned area and appears to be strongest closest to the fuel for fires.

Eighty-eight percent (14/16) and 42% (8/19) of the extracts from $A_1$ horizon samples collected from washes leading downslope from 1- and 2-yr-old burned areas at sites 4 and 5, respectively, significantly stimulated germination (all $F > 6.9, P < 0.0001$; Fig. 1B, C). All samples collected in the wash leading from the 1-yr-old burn (Fig. 1B), had significantly increased germination ($P < 0.001$), except for one collection from within the burn ($P = 0.084$) and one outside the burn ($P = 0.115$). The germination potential of $A_1$ soil horizons collected from the wash leading from the 2-yr-old burn was more variable. Of the eight collections that had significantly increased germination, three were from within and five were from outside the burned area. Interestingly, the samples collected 1 km downslope from the burned area elicited a significant germination response. Site differences in slope and fire history make comparisons between washes difficult; however, these results demonstrate the long-distance transport of smoke-derived germination signals at great distances downslope into unburned areas, most likely by water.

Eighty percent (16/20) of the $A_1$ horizon samples collected along the upwind transects at the 1-yr-old burn significantly stimulated germination more than did water, including the two samples collected ~20 m into the adjacent unburned area ($F_{20,42} = 28.37, P < 0.0001$; Fig. 1D, E). Sixty-seven percent (4/6) of the samples collected along the downwind transect significantly stimulated germination ($F_{6,14} = 16.035, P < 0.0004$; Fig. 1F). The two samples collected at the greatest distances (30 and 40 m) elicited significant germination responses. Because no rain had fallen during the intervening week between the fire and the soil collections, we conclude that the smoke germination cue can be transported by wind over large distances from burned areas into adjacent unburned areas.

Extracts of $A_1$ horizon samples collected from burned areas ≤7 yr old resulted in significant germination responses ($F_{8,18} = 15.807, P < 0.0004$; Fig. 2). Collections from 2- and 3-yr-old burns (sites 5 and 7; Fig. 2) had marginally significant responses after the Bonferroni adjustments of significance levels (0.0064 and 0.0038, respectively; $P_{adj} = 0.0014$). Bioassays treated with extract of the $A_1$ horizon collected at site 10, believed to be at least a 30-yr-old burn, had fewer seeds germinating than did the water-treated control bioassays ($P = 0.0002$; Fig. 2). All extracts from $A_1$ soil horizons collected from unburned areas adjacent to the different-aged burned areas elicited germination at levels that were not significantly different than that elicited by water ($F_{6,14} = 4.789, P > 0.1055$), with the exception of a collection adjacent to a 1-yr-old burn at site 2 ($P < 0.0001$). This sample may have been contaminated by the cue leaching through runoff from a small burned area located upslope of the collection site. We conclude that the smoke-derived germination cue can be transported by wind and water out of the burned area, but is largely contained within the burned area. However, the cue can exist in soils of burned areas for substantially longer than the 3-yr post-fire time period when *N. attenuata* plants are commonly found (see Introduction).

**Effects of $A_0$ extracts on germination.**—Aqueous extracts of all litter-containing $A_0$ soil horizons (with and
Catherine A. Preston and Ian T. Baldwin

Fig. 3. Mean (±1 SE) germination percentages of *N. attenuata* seeds in bioassays treated with extracts of *A.0* soil horizons collected from under seven species that represent the majority of the aboveground biomass found in unburned areas. Each treatment had three replicate bioassays of 20 *N. attenuata* seeds. All seeds, except those used in the water-treated control bioassays, were soaked for 1 h in 1:300 liquid smoke before being placed in bioassay containers containing *A.0* extracts without dilution (●), or diluted 1:10 with distilled water (○). Without dilution, bioassays received an amount of extract approximately equivalent to 1 cm³ of *A.0* soil horizon. Germination percentages for water- and smoke-treated control bioassays are also depicted (▲).

Effects of *A.0* horizon on germination.—Because seeds in natural seed banks may or may not be in direct contact with leaf litter of the *A.0* horizon, we compared the effects of direct and indirect contact with *JA*.horizon on the germination of seeds previously exposed to wood smoke. All treatments significantly reduced germination responses below those of the smoke controls (*F*₁₅.₃₂ = 41.966, *P* < 0.0001; Fig. 3). Germination responses from all *A.0* horizon extracts, when applied without dilution, were not statistically different from the background germination rate observed in water-treated seeds (*P* > 0.1924). We conclude that extracts of the *A.0* horizon from unburned vegetation will prevent the germination of *N. attenuata* seeds exposed to a smoke cue, even at a 10-fold dilution.

Precedence of + and – germination cues.—Fig. 6A depicts the germination percentages of seeds treated with smoke extract (+) for different lengths of time before being transferred to containers with JA. horizon (−). Seeds exposed to (+) for ≥48 h did not germinate when moved to an environment with (−), and had significantly fewer seeds germinating than did water controls.

In a separate experiment with burned soil (instead of smoke-treated seeds in sand), we added ground JA. horizon in increasing increments below the burned JA. horizon to determine when the negative effect of the JA. horizon would override the positive effect of the JA. horizon (Fig. 5). Germination was reduced to 20% with the presence of 0.5 cm³ of JA. horizon underneath a 2 cm³ burned JA. layer, and to nearly 0% with greater volumes of JA. horizon. Germination in the presence of the JA. horizon was significantly lower than that with soil and water alone (*F*₆.₁₄ = 72.910, *P* < 0.0001), and with ≥1 cm³ of JA. horizon, germination was lower than that observed in the water controls (*P* < 0.0005). We conclude that the presence of an JA. horizon from species commonly found in the latter stages of post-fire succession can inhibit the germination of *N. attenuata* seeds even if the positive smoke-derived germination cue is in the soil.

Fig. 4. Mean (±1 SE) germination percentages at Day 7 of three replicates of 20 *N. attenuata* seeds in each of four spatial arrangements with the JA. horizon collected from underneath unburned juniper trees. Seeds were placed either above or below the JA. horizon, which was either left intact or ground in a Wiley mill, as depicted in the diagram. In all treatments, seeds were soaked in 1:300 liquid smoke for 1 h before being placed on a layer of sand. The seed cups were moistened with additional 1:300 liquid smoke until the sand was saturated. Treatments with ground JA. soil horizon completely inhibited germination.
POSITIVE AND NEGATIVE GERMINATION SIGNALS

March 1999

FIG. 5. Mean (± 1 se) germination percentages at Day 14 for seeds placed on 2 cm³ of burned soil (collected from site 2; Table 1), above different volumes (0–3 cm³) of ground A₀ horizon collected from underneath juniper. Thus, seeds were not in direct contact with the A₀ horizon. Water controls contained only 2 cm³ of sterile sand to provide background germination values. All treatments were saturated with distilled water, and each treatment had three replicate bioassays, each with 20 N. attenuata seeds.

FIG. 6. Mean (± 1 se) germination percentages for seeds exposed to positive-to-negative vs. negative-to-positive transfers. (A) Seeds treated on Day 0 with 1:300 liquid smoke (+) were transferred to new containers with extract of the A₀ horizon collected under juniper (−) on Days 1–6. (B) Seeds treated on Day 0 with extract of the A₀ horizon collected under juniper (−) were transferred to new containers with 1:300 liquid smoke (+) on Days 1–6. The inset in (B) depicts viability (mean germination percentage ± 1 se) of seeds that had not germinated for 9 d after (−) to (+) transfer. Viability was defined as germination within 19 d after the seeds had been soaked in a 5% hypochlorite solution for 2 min to scarify the seed coat.

(P < 0.0001). However, after a 48-h exposure to (+), germination was not inhibited by (−) (Fig. 6A). Seeds initially exposed to (−) and transferred to containers with (+) germinated at levels significantly lower than water controls (P < 0.0001; Fig. 6B). The (−) did not kill seeds; when these seeds were scarified with a short exposure to hypochlorite, 54–87% of the dormant seeds germinated after 19 d (Fig. 6B, inset). We conclude that the inhibitory effect of the A₀ horizon on germination functions at the initial stages of seedling development before the radicle emerges from the seed coat. Once the seed has been exposed to the smoke cue for >48 h, A₀ horizon components can no longer prevent germination. However, if the seeds are first exposed to extracts of the A₀ horizon, they do not germinate when moved to an environment with only the smoke cue, possibly indicating that the A₀ horizon extracts prevent the binding of the (+) cues to the seed. The A₀ horizon extracts are not toxic to the seeds, but rather enforce their dormancy.

Seed bank experiment.—The cumulative number of seedlings germinating from seed banks treated with smoke extract was significantly higher than all other treatments, whereas seed banks treated only with A₀ horizon extracts had significantly fewer seedlings germinating than those treated with water (F₁,₄₅ = 15.749; P < 0.0001; Fig. 7). When seed banks were treated with either a 1:1 combination of smoke extract (+) and JA₀ Ex (−) or (+) two days before (−), to produce environments with both signals, the cumulative numbers of seedlings germinating were not significantly different from seed banks treated with water (P > 0.1456). Additionally, seed banks treated with the 1:1 combination of (+) and (−) cues had significantly more seedlings germinating than did seed banks treated with only the (−) cue (P = 0.0005), but not more than the seed banks receiving (+) before the (−) (P = 0.1038). We conclude that the extracts of the A₀ horizon inhibit nondormant individuals in a natural seed bank, suppressing germination below that of water-treated controls when no smoke cue is present. Moreover, when a smoke cue is added to the soil, either before or concurrent with A₀ horizon extracts, the negative effects of the A₀ horizon extract override the positive effects of the smoke cue.

Effects of A₀ horizon on growth and lifetime seed production.—Fig. 8 depicts the consequences for lifetime seed production of growing in unburned soil, burned soil, or burned soil amended with either JA₀ Ex or ground JA₀. Seedlings grown in burned soil, with or
Germination response in replicate seed banks under different treatments: (+), 1:100 smoke, 20 replicates; (−), extract of the A<sub>0</sub> horizon collected under juniper (JA<sub>0</sub>Ex), 30 replicates; (control) distilled water, 20 replicates; (+) and (−), a 1:1 v/v mixture of 1:50 liquid smoke and JA<sub>0</sub>Ex, 10 replicates; and (+) to (−), 1:100 liquid smoke followed 2 d later by JA<sub>0</sub>Ex, 10 replicates. Values are the cumulative mean numbers of <i>N. attenuata</i> seedlings germinating after 24 d for each treatment (± 1 se).

Germination effects of JA<sub>0</sub>Ex on a nondormant tobacco species.—On Day 8, germination of seeds of a nondormant tobacco species, <i>N. trigonophylla</i>, was not significantly different in JA<sub>0</sub>Ex as compared with nutrient controls (F<sub>1,4</sub> = 1.323; P = 0.3141), whereas JA<sub>0</sub>Ex significantly reduced germination of <i>N. attenuata</i> (F<sub>1,4</sub> = 31.890; P = 0.0048; Fig. 9). We conclude that the extracts produced from the A<sub>0</sub> horizon affect only the germination response of the dormant tobacco, <i>N. attenuata</i>, and not the conspecific, nondormant tobacco, <i>N. trigonophylla</i>.

**Discussion**

When <i>Nicotiana attenuata</i> seedlings germinate and grow in burned soil in the glasshouse, their lifetime seed production is 12 times greater than it is if they germinate in unburned soil (Fig. 8), reflecting the 40-fold differences in available nitrogen in these soils (Lynds and Baldwin 1998). Moreover, when potted <i>N. attenuata</i> plants are placed in freshly burned juniper habitats, the amount of leaf area consumed by herbivores is 1–20 times less than that of plants placed in adjacent unburned habitats (I. T. Baldwin and L. Morse, *unpublished data*). Hence, this species clearly gains a large fitness benefit by synchronizing its germination and growth in recently burned areas (Baldwin 1998). The distribution of <i>N. attenuata</i> populations in nature is consistent with its germination and growth being regulated by habitat-specific signals, because it is found without A<sub>0</sub> horizon amendments, produced more capsules, heavier capsules, and heavier seeds (F<sub>3,24</sub> = 17.26, 8.770, and 11.975, respectively; P < 0.0002) than did those seedlings grown in unburned soil. From these parameters, the estimated lifetime seed production of plants growing in burned soil (5181 ± 916 seeds per plant, mean ± 1 se) was 12-fold higher than that of plants growing in unburned soil (385 ± 146 seeds per plant). We conclude that JA<sub>0</sub> or JA<sub>0</sub>Ex in concentrations sufficient to completely inhibit germination do not have any fitness consequences for plants once they have germinated. The accumulation of an A<sub>0</sub> soil horizon provides signals that influence germination, but does not inhibit the growth of plants after germination. The fitness cost to <i>N. attenuata</i> of germinating in an unburned environment is clearly very high.

<i>N. attenuata</i> is an aggressive invasive species that is widely distributed in its native distribution (Baldwin and Knapp 1998). The ability of this species to germinate in burned areas is one of the factors that allow it to establish in new habitats. The ability of <i>N. attenuata</i> to germinate in burned areas may be important for its invasion of new habitats, because the amount of leaf area consumed by herbivores is 1–20 times less than that of plants placed in adjacent unburned habitats (I. T. Baldwin and L. Morse, *unpublished data*). Hence, this species clearly gains a large fitness benefit by synchronizing its germination and growth in recently burned areas (Baldwin 1998). The distribution of <i>N. attenuata</i> populations in nature is consistent with its germination and growth being regulated by habitat-specific signals, because it is found without A<sub>0</sub> horizon amendments, produced more capsules, heavier capsules, and heavier seeds (F<sub>3,24</sub> = 17.26, 8.770, and 11.975, respectively; P < 0.0002) than did those seedlings grown in unburned soil. From these parameters, the estimated lifetime seed production of plants growing in burned soil (5181 ± 916 seeds per plant, mean ± 1 se) was 12-fold higher than that of plants growing in unburned soil (385 ± 146 seeds per plant). We conclude that JA<sub>0</sub> or JA<sub>0</sub>Ex in concentrations sufficient to completely inhibit germination do not have any fitness consequences for plants once they have germinated. The accumulation of an A<sub>0</sub> soil horizon provides signals that influence germination, but does not inhibit the growth of plants after germination. The fitness cost to <i>N. attenuata</i> of germinating in an unburned environment is clearly very high.

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primarily in the immediate post-fire environment (Young and Evans 1978). Pierce et al. (1995) found that, in the Mesembryanthemaceae family, many succulents germinated in response to smoke, irrespective of whether they were found in fire- or non-fire-prone habitats of South Africa, and questioned the ecological significance of smoke as a germination signal. This is not the case for tobacco, as other species of Nicotiana do not exhibit an enhanced germination response when exposed to the smoke-derived cue (Baldwin et al. 1994). However, from our analysis of the location of the smoke-derived germination cue in the field, seeds cannot reliably identify the post-fire environment by the presence of the cue alone. We found the cue (1) to be heterogeneously distributed within a burned area, with quantities in the soil varying with their proximity to burned vegetation (Fig. 1A); (2) to be transported (probably by both wind and water) into adjacent unburned areas in quantities sufficient to germinate dormant seeds (Fig. 1B–F); and (3) to reside in soils of burned areas for ≥7 yr (Fig. 2), which is 4 yr longer than the realized niche for this species (see Introduction). We did not find evidence of the germination signal in any of the eight sites that had not had a fire in the past 30 yr, indicating that the smoke cue does deteriorate with age and is not found everywhere. However, the cellulose combustion products that signal germination in N. attenuata seed banks are distributed in nature far more broadly than the plant’s germination niche, indicating that other factors must regulate germination from these long-lived seed banks.

We demonstrate the existence of negative, germination-inhibiting factors in the A₀ horizon of soils from unburned areas. Our experiments show that these negative signals: (1) are found in the litter-containing A₀ horizon of seven species that dominate the vegetation growing in these habitats later in succession after fires (Fig. 3); (2) are water soluble and seeds do not require direct contact with the litter-containing A₀ layer for seeds not to germinate (Fig. 4); (3) can completely inhibit the germination of seeds as long as the seeds have not been exposed to the smoke cue for >48 h and the radicle has not emerged from the seed coat (Fig. 6A); (4) function to inhibit germination at concentrations that are neither toxic to seeds (Fig. 6B) nor inhibit the growth of mature plants or their reproductive output (Fig. 8); (5) suppress germination of nondormant N. attenuata seeds (seeds that do not require exposure to smoke to initiate germination) (Fig. 7); and (6) do not inhibit the germination of a nondormant species of tobacco, N. trigonophylla (Fig. 9), which is not associated with fires. Although these germination inhibitors profoundly enforce dormancy in N. attenuata, they have no toxic effects on seed viability and plant growth and are unlikely to be allelopathic agents mediating competitive interactions among plants. We conclude that these negative regulators of germination are likely to function solely to temper the germination responses to the smoke factors and to focus germination to the post-fire habitat during the 2–3 yr phenological window before successional regrowth produces a new A₀ soil horizon.

We propose that the distribution of populations of N. attenuata in nature can best be understood as being partly a consequence of both positive and negative control over the germination from long-lived seed banks. Fire pyrolyzes the litter-containing A₀ horizon and the constituents that inhibit germination, leaving the positive germination signals in the smoke to stimulate germination within the burned area. Germination of N. attenuata requires the smoke signal and is not controlled solely by the removal of litter by a fire (i.e., it is not merely the presence or absence of the negative cue that signals germination), as shown by the negligible germination in the water-treated control bioassays, where seeds have never been exposed to litter (Figs. 3–5). The majority of the input of seeds into the seed bank occurs during the first 3 yr after a fire, as seeds accumulate in the exposed A₁ layer of the burned soil and come in contact with the smoke signal, which
is present in the soil for ≥7 yr after a fire. However, germination does not continue after the 3 yr post-fire window. This is due, in part, to the negative factors leaching from the newly developing, litter-containing A₀ horizon above the seed-containing A₁ horizon. Wind and water transport of the smoke cue does not stimulate germination in adjacent unburned areas, because the litter-derived factors are able to override the positive effects of the smoke cue and thereby preserve the dormancy of these seed banks. Other disturbances that remove the A₀ horizon and its suppression of the seed banks, such as road construction, can result in a germination response from the seed bank and the appearance of ephemeral populations. Areas where the A₀ horizon does not accumulate, as in washes, will allow for persistent populations of nondormant individuals or dormant individuals responding to smoke signals leached from burned areas upslope.

Although fire-associated release of dormancy involves physical scarification of the seed coat for some species (Atwater et al. 1980, Brits et al. 1993, Qi et al. 1993), or the oxidation of seed coats (Keeley and Fotheringham 1997), the response of dormant seeds may be much more complicated than these physical mechanisms imply. For example, exposure of *Emmenantha penduliflora* to oxidizing gases does not increase the water permeability of the seed and, therefore, is not a simple scarification of the seed coat (Keeley and Fotheringham 1997). Similarly, the smoke cue that stimulates germination in *N. attenuata* appears to be a specific germination signal (Baldwin et al. 1994). We are presently identifying the component(s) of wood smoke that stimulate germination in dormant *N. attenuata* populations. Keeley and Fotheringham (1997) have recently suggested that nitrogen oxides are the components of smoke that are responsible for initiating germination in dormant seeds of the California chaparral species, *E. penduliflora*. However, our laboratory’s investigations utilizing GC/MS (gas chromatography/mass spectrometry) to separate smoke fractions and NMR (nuclear magnetic resonance) techniques on an active peak have elucidated a structure in the active fraction that is composed of carbons, hydrogens, and oxygens (I. T. Baldwin and Zhang, unpublished data). This ecological investigation provides valuable information about the nature of the smoke-derived germination signal, against which a synthesized structure can be tested.

The inhibitory factors are also likely to be specific signals. Although the litter of several species has been found to inhibit germination (Mayer and Poljakoff-Mayber 1989), and many phenolics and terpenoids found in litter are known to inhibit germination (Koves and Varga 1958, Inderjit and Dakshini 1995), the chemical basis of this process is not understood. Substances identified as germination inhibitors in some species may function as germination promoters in other species, or in the same species at different concentrations. Jasmonic acid, a ubiquitous wound signal in plants (Karban and Baldwin 1997), can function as both an inhibitor (Gross and Parthier 1994) and a stimulator (Berestetzky et al. 1991). Similarly, some allelochemicals are generally accepted as stimulators at low concentrations and as inhibitors at high concentrations (An et al. 1993).

Keeley and Fotheringham (1997) speculated that dormant seed banks of *E. penduliflora* may be “tricked” by inputs of nitrogen oxides from anthropogenic pollution, and may germinate in unburned habitats. Although such a potentially maladaptive germination response may occur in *E. penduliflora*, *N. attenuata*, with its combined positive and negative control over germination, is clearly assessing its environment in a more sophisticated fashion and would not be “tricked” into germinating. Dormant seeds are very likely utilizing a diverse suite of chemical signals provided by their environment to signal germination. We propose that many species use both positive and negative controls over their germination responses, and that the ubiquitous negative effects of litter and plant exudates on germination, but with little negative effects on subsequent growth, argue forcefully for the interpretation that these negative effects are due to signal perception rather than allelopathically mediated competition between plants.

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