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Repeated Selective Cutting Controls Neotropical Bracken (*Pteridium arachnoideum*) and Restores Abandoned Pastures

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Neotropical bracken fern invades disturbed forests and burned and abandoned pastures in Latin America, inhibiting the growth of associated vegetation and altering community structure. Cutting of all aboveground vegetation every 6 to 12 mo has proven to be inefficient as a control method. We studied the impact of selective cutting of bracken every 2 mo, shading, and a combination of cutting + shading during 14 mo in a bracken-dominated, abandoned pasture in Veracruz, Mexico. At the end of the experiment, cutting with or without shading drastically reduced bracken cover from >90% to less than 1%, decreased leaf number from 18 to fewer than two leaves per m^2, and depleted bracken leaf biomass. The significant reduction of bracken was correlated with a significant 3.9- to 5.7-fold increase in richness of other plant species. Cutting without shading was the only treatment that significantly reduced rhizome biomass to less than 62% of control plots, whereas cutting + shading was the only treatment to promote a significant increase in both cover and shoot biomass of successional plant species. Selective cutting of *P. arachnoideum* repeated every 2 mo was more successful than nonselective cuttings repeated at longer intervals, because it removed newly emerging leaves before their complete expansion and supported the recovery and reestablishment of other plant species, which may help to control bracken. Although costs for the first year of selective cutting were twice as much as for nonselective cutting, it may prove less expensive and more efficient than nonselective cutting in the long term.

Nomenclature: Bracken, *Pteridium* spp.; Neotropical bracken fern, *Pteridium arachnoideum* (Kaulf.) Maxon.
Key words: Dennstaedtiaceae, ferns, invasive plants, mechanical weed control, restoration, rhizome, shading.

Less than 1% of the 9,500 terrestrial fern species worldwide are considered invasive (i.e., aggressive weeds, not necessarily exotic), and most of those species belong to the families Gleicheniaceae and Dennstaedtiaceae (Robinson et al. 2010). Members of these two families typically have a fast growing, creeping, branching and subterranean rhizome, exposing only their leaves (i.e., fronds) aboveground. Because of this growth form, these species are difficult to control with herbicides. Some bracken ferns (*Pteridium* spp., Dennstaedtiaceae), are perhaps the most noxious of these invasive species. Once established in large stands, their long-lived, branching rhizomes form huge clones (Atkinson 1989). In Finland, Oinonen (1967) estimated bracken clones of about 250 m (273.4 yd) diameter to be 700 yr old. Bracken leaves produce a dense canopy that inhibits growth of shade intolerant species and a dense layer of leaf litter that buries seeds and seedlings, and may arrest any further succession to secondary forests for decades (Marrs et al. 2000; Marrs and Watt 2006; Robinson et al. 2010). Furthermore, leachates and extracts of old, retained leaves suppress seed germination through the release of allelopathic compounds (Gliessman 1976; Gliessman

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Management Implications

The selective cutting of bracken leaves and the removal of all leaf litter is a viable strategy to restore abandoned, bracken-infested pastures. Selective cutting of bracken promotes the establishment and recovery of pasture species, which help to control bracken. Repeated cutting should be performed according to the rate of bracken regrowth at each site and should always be applied before newly emerging leaves have completely expanded and begun to return photosynthetic products back into the rhizome. After six subsequent cuttings, bracken cover should be less than 1%. In tropical humid climates, cutting should be performed up to six times per year because of continuous plant growth throughout the year. Monitoring the reduction of the rhizome biomass within 1 m soil depth may serve as an indicator of the success of treatments. Trenches of 1 m in depth dug along the peripheral zone may halt further vegetative expansion of bracken rhizomes.

and Muller 1978; Wang et al. 2011). In Mexico, at least two of the six native taxa (Mickel and Smith 2004) also form dense, monospecific stands, often promoted by forest clearings as well as by fire and abandonment of pastures: *P. caudatum* (L.) Maxon (Ramirez-Trejo et al. 2010) and *P. arachnoideum* (Kaulf.) Maxon (K. Aguilar, personal observation).

Recent land-use changes have led to an increase in the distributional range of *Pteridium* species in various parts of the world (Royo et al. 2010). For example, in Brazil, *P. arachnoideum* invades areas of rough grazing after deforestation (Silva-Matos and Belinato 2010), whereas in Ecuador, pastures have been abandoned because of bracken infestation, which now covers approximately 68% of these areas (Beck et al. 2008). In temperate climates, such as in Great Britain, another bracken species, *P. aquilinum* (L.) Kuhn, may expand at rates of 1 to 3% annually and was estimated to cover between 2.8% (Taylor 1986) and 7.3% (Pakeman et al. 1995) of the land surface.

Effective control of invasive *Pteridium* species is extremely difficult and currently requires continuous treatment over many years (Marrs et al. 1998). Two strategies are commonly used for bracken control: (1) Chemical control refers to the application of herbicides, such as glyphosate (Baylis 2000), which may reduce leaf density of *P. aquilinum* more than 95% following two applications per year (Ghorbani et al. 2007). (2) Mechanical control usually refers to nonselective cutting of aboveground material, which may be repeated two or three times annually (Marrs et al. 1998; Roos et al. 2010), and is perhaps the most labor- and cost-intensive management regime. Whereas chemical management with broad-spectrum herbicides such as glyphosate suppresses most of the bracken-associated vegetation, newly suggested integrated methods promote the development of competitive vegetation that can help in controlling bracken (Pakeman et al. 2000).

Pastures occupy 45% of the State of Veracruz, Mexico and 16.1% of the Mexican territory (INEGI 2012). Burning is a common management practice of pastures to rejuvenate grasslands and control woody vegetation. However, fire also promotes bracken invasion, and pastures are often abandoned once they are completely infested by bracken. Consequently, the aim of our study was to reconvert bracken-invaded land back into pastures composed of a diverse community of grasses and herbs. Therefore, we determined the effect of two bracken control methods that conserve and promote associated vegetation: (1) repeated selective cutting of *P. arachnoideum* and (2) shading with 70% shade cloth. We hypothesized that repeated selective cutting would break the dominance of light-demanding bracken over associated species allowing for the restoration of shade intolerant pasture species in cutting treatments without shade. We also hypothesized that the shading treatment with 70% shade cloth would weaken the competitiveness of light-demanding bracken to the benefit of more shade-tolerant pasture species. Because some of the pasture species are light-demanding, shading treatments as a management method would be temporary and would be removed after successful bracken control. Our study aimed to quantify the impact of our control methods on ground cover and rhizome biomass of neotropical bracken to assess the effectiveness of control strategies against different bracken species in temperate and tropical regions. In addition, we want to identify an integrated method that avoids the use of herbicides but takes advantage of associated plant species, to stop the further spread of invasive neotropical bracken, which is toxic to cattle (Evans et al. 1982, Wilson et al. 1998).

Materials and Methods

Study Site and Species. The study site was located within an old pasture, abandoned about 50 yr ago, near the town of Huatusco, Veracruz, Mexico (19°11′01″N, 96°59′25″W, 1300 m a.s.l.). With the exception of some scattered trees and shrubs, over 90% of the vegetation cover at the study site comprised *P. arachnoideum* of over 2 m height. This bracken species could be distinguished easily from *P. caudatum*, the other common bracken species in Mexico, by free lobes between the last segments near pinnae apices (Mickel and Smith 2004). The study site was surrounded by pastures with isolated trees, fragments of the original cloud forest, and some secondary vegetation. Soils were andisols and acrisols, poor in K, Ca, and Mg, with a pH ranging between 4 and 5 (Geissert and Ibáñez 2008) and covered by a litter layer of ca. 10 cm depth (3.94 in), mainly consisting of bracken litter. The soil profile followed a sequence of three horizons A1-A2-A3/C (IUSS Working Group WRB 2007) of similar field capacities of water retention at 30 kPa: A1 (0 to 25 cm) = 0.44 m^3/m^3, A2 (25 to 50 cm) = 0.39 m^3/m^3, and A3/C (50 to 100 cm) = 0.40 m^3/m^3 (D. Geissert, 2013, Instituto de Ecología, A.C., Xalapa, personal communication). Mean annual temperature at the weather station Huatusco was 19.6 C (67.3 F) and mean annual precipitation was 1,997 mm (78.6 in) with a dry season from November to April (monthly mean 18.1 C, 55.3 mm/mo) and a rainy season from May to October (21.0 C, 277.6 mm/mo; Comisión Nacional del Agua 2013).

Pteridium arachnoideum is the bracken species with the widest geographic distribution within the New World, ranging from Mexico, the Caribbean and Central America, south to Argentina. In Mexico, *P. arachnoideum* grows in open, disturbed areas between 100 and 2,450 m elevation with leaves reaching 1.5- to 3 m height (Mickel and Smith 2004). Voucher specimens were collected at the study site, identified with taxonomic keys from Mickel and Smith (2004) and deposited at the herbarium of the Instituto de Ecología, A.C., Xalapa (XAL).

Experimental Design. We conducted the experiment from June 2010 to August 2011, using a randomized block design with two crossed factors: shading with cloth and cutting with machete or pruners at soil level. Along a trail, we selected treeless areas on a smooth 0 to 10° SE-facing slope with a bracken cover $>90\%$ and height of >2m. Experimental blocks were marked in these areas using wooden stakes to define five blocks of 7 by 7 m, separated by at least 20 m distance from each other. Larger block sizes were not possible because larger blocks would have put some treatments adjacent to trees and shrubs and would have been affected by shade and by greater root interactions. Each of the blocks comprised four plots of 2 by 2 m, one for each treatment (Figure 1a): control (X), shading (S), cutting (C), cutting + shading (CS). Plots were separated from each other and from the surrounding area by 1 m wide buffer zones, which were kept free of *P. arachnoideum* by cutting all emerging leaves every 2 mo. These buffer zones isolated treatment plots within blocks and standardized experimental disturbance when plots had to be accessed for subsequent treatments and measurements. The small plot size of 2 by 2 m was necessary to count leaf numbers and to cut exclusively bracken leaves without any further disturbance of the plots, comparable to Roos et al. (2010) who had already used circles of 2 m diam for the repeated measurement of leaf growth. Each plot was surrounded by a black polyethylene foil of 0.055 mm thickness (calibre 220), inserted 30 cm into the soil to interrupt any connection of rhizomes within the uppermost 30 cm of the soil across treatments or buffer zones and to restrict treatment effects on the bracken rhizome network of individual plots. A spade was used to cut a line 30 cm deep around each plot, without extracting any soil or rhizomes, but cutting all crossing bracken rhizomes. Then we inserted the plastic foil with use of the spade and secured it by adding and compacting soil from the side of the buffer zone. The plastic foil could not be placed deeper into the soil without disturbing the original vegetation. Treatments were randomly assigned to plots within each block. Control plots were left in natural conditions, except for the delimitation with plastic foil.

Shading was achieved by placing a black polyethylene cloth of 70% shading (13 by 8.5 threads cm^{-2}, Deniers 630, Asesores en Construcción y Extensión Agrícola S. A. de C. V., Mexico) on top of four wooden stakes secured at each corner of the two corresponding plots, covering S and CS treatments under a single tent (Figure 1c). Shade cloth was placed arbitrarily at 1.5 m height, even if it suppressed the largest leaves mechanically, and hung down 25 cm on each of the four sides. Although these shade tents could not avoid some minor edge effects, we preferred this option rather than closing all sides of shade tents, which would have caused undue warming or ventilation effects. Cutting consisted of selective removal of *Pteridium* leaves every 2 mo, by cutting them at surface level, with the exception of the first cut (June 2010) when all aboveground vegetation including leaf litter was removed, leaving a bare soil surface. Removal of the dense layer of leaf litter of about 10 cm thickness was essential to reduce potential allelopathic effects and to promote the establishment of successional plant species from dispersed seeds or from the seed bank.

Every 2 mo we measured ground cover, number of leaves, and maximum height of bracken in all treatments, starting in August 2010. Aboveground leaf biomass of bracken (only in cutting treatments) was harvested, dried for 72 h in an oven at 70 C, and then weighed. To minimize edge effects, all measurements were performed exclusively within the central 1 m^2 of each plot to minimize edge effects, although treatments were applied to the entire 4 m^2 of the plots.

After 14 mo, cover and dry aboveground biomass of all species were measured for all treatments. First, we measured cover and harvested aboveground leaf biomass of bracken avoiding any disturbance to other plants species. Then, we measured cover of all other plant species, harvested their aboveground leaf biomass, dried it for 72 h in an oven at 70 C, and weighed it. During earlier stages of the experiment, cover of other plant species would have been difficult to assess because of the dense bracken thicket in treatments without cutting, and the destructive assessment of dry aboveground biomass would have interfered with our ability to study succession over the entire duration of the experiment. In addition, bracken rhizomes were harvested in three layers from 0 to 30, 31 to 60 and 61 to 90 cm soil depth by digging pits in the central 1 m^2 of each treatment at the end of the experiment (Figure 1a). Removed soil material was examined by hand

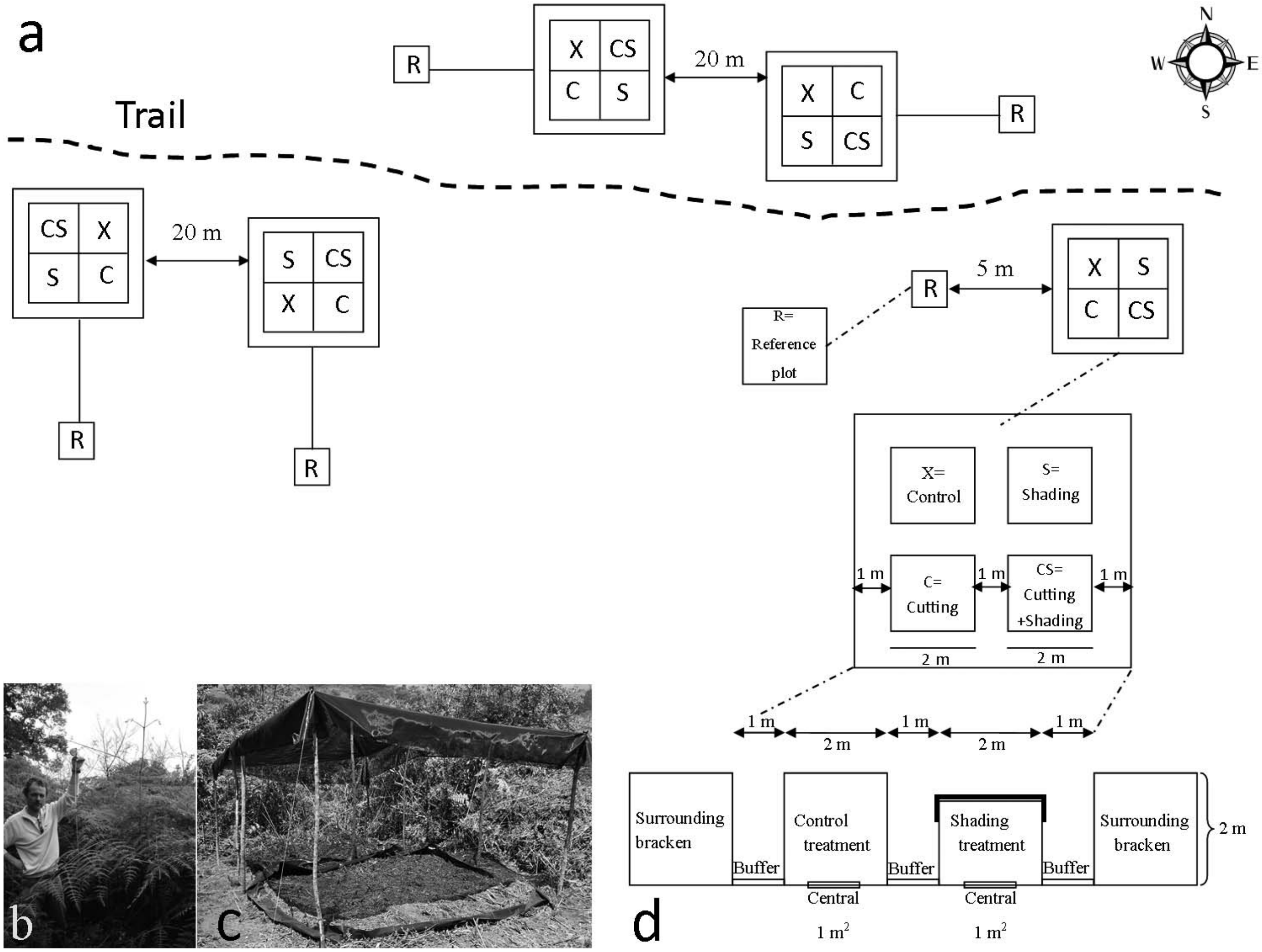

Figure 1. (a) Experimental design of randomized blocks, each with four treatments, (b) undisturbed site before the experiment, showing bracken cover and height, (c) shade tent, (d) lateral view of an experimental plot to scale. Control treatments within blocks (X) experienced the same rhizome isolation procedure using plastic foil and buffer zones as applied in the other treatments. External reference plots (R, outside the block) were totally undisturbed.

to collect all bracken rhizomes. Rhizomes were brushed to remove soil and other organic matter and dried in an oven for 72 h at 70 C. To measure bracken biomass without any interference of the experimental treatments, such as the delimitation by plastic foil and establishment of buffer zones, bracken biomass of leaves and rhizomes of five external reference plots of 1 m^2 were harvested in April 2011 at $\geq$5 m distance from each experimental block to avoid any interference (external reference plots [R], Figure 1a).

Cost estimates. We estimated annual costs of labor and material per ha for cutting and shading treatments. Required labor hours for specific activities were set by the Mexican Government (Diario Oficial de la Federacion 2011). For the calculations, we applied commonly paid daily wages for farm laborers of 14 USD per day at the current exchange rate. For the cost of bulk shade cloth (70% shade, black), we considered a price of 1.8 USD per m^2, for lightweight cable a cost of 0.042 USD m^{-1}. Wooden stakes for the construction of the shade tents were not included in the calculations, because landowners typically use wood from their own ranches to save costs. For herbicides (glyphosate), we considered a price of 12.5 USD L^{-1} and for a herbicide backpack of 50 USD.

Statistical Analyses. Treatment effects related to *P. arachnoideum* measured after 14 mo as well as those related to successional plants were subjected to mixed model analysis of variance (ANOVA) on leaf number, leaf biomass, rhizome biomass, cover, and maximum height, with shade and cutting as fixed factors with two levels each and block as a random factor, followed by a Tukey multiple comparison procedure ($P < 0.05$). The distributions of leaf and rhizome biomass of bracken as well as shoot biomass of successional plants were normalized by log-transformation, percentage of ground cover of all plants was arcsine transformed and leaf number was square-root transformed prior to ANOVA. In addition, final rhizome biomass was subjected to mixed model ANOVA to test for differences among treatments and levels of soil depth. A two-way crossed analysis (ANOSIM2; Clarke and Gorley 2001; Clarke and Warwick 2001) was performed to test for significant differences in species composition among treatments and blocks. Statistics were performed with Statistica ver. 7.1 (StatSoft, Tulsa, Oklahoma, USA), with the exception of ANOSIM2, which was conducted in PRIMER 5 (Primer-E Ltd, Roborough, Plymouth, UK).

Results

Treatment Effects on bracken. At the beginning of the experiment, *P. arachnoideum* cover in control plots (X) was over 90% (Figure 2a), with more than 18 leaves per m^2 (Figure 2b) and a maximum height of 2.2 m (Figures 1b, 2c). After 14 mo, C and CS plots exhibited significant reductions in bracken cover ($F_{[1,12]} = 59.02$, $P < 0.001$), leaf number per m^2 ($F_{[1,12]} = 39.40$, $P < 0.001$), maximum height ($F_{[1,12]} = 9.22$, $P = 0.010$; Figure 2), and leaf biomass ($F_{[1,12]} = 62.11$, $P < 0.001$; Table 1) compared to control plots. However, the decrease of rhizome biomass was only significant in C plots compared to that of the control treatment (Tukey, $P = 0.036$; Table 1).

Leaves of *P. arachnoideum* had a mean height of 1.4 m in C and CS treatment plots after 2 mo (August) and the majority of laminae had not started to expand. After 6 mo, at the beginning of the dry season in December, leaf cover of bracken in C and CS treatments was less than 20%, and after 10 mo less than 10%. The beginning of the rainy season after 2 mo (June) did not significantly alter the treatment effects and after 14 mo cover was less than 1% (Figure 2a). Although leaf numbers in C and CS treatments recovered temporarily after three cuttings (6 mo), there were fewer than 4 leaves per m^2 after 10 mo and fewer than 2 leaves per m^2 after 14 mo with a maximum height of about 1 m; 50% less than in the control treatment (Figure 2b). In the S plots, leaf cover (Figure 2a), leaf number (Figure 2b), leaf height (Figure 2c), and leaf and rhizome biomass of bracken were not significantly different from those of the control plots (Table 1).

Leaf biomass responded faster to cutting treatments than leaf cover. Leaf biomass in C and CS treatments was less than 25% of that observed in the control plots (X, 579 ± 99 g m^{-2}) in the 2 mo sample, and less than 2.5% in the 8 to 14 mo samples (Figure 3). Leaf biomass did not increase significantly following the beginning of the rainy season, in the 12 mo sample (Table 1).

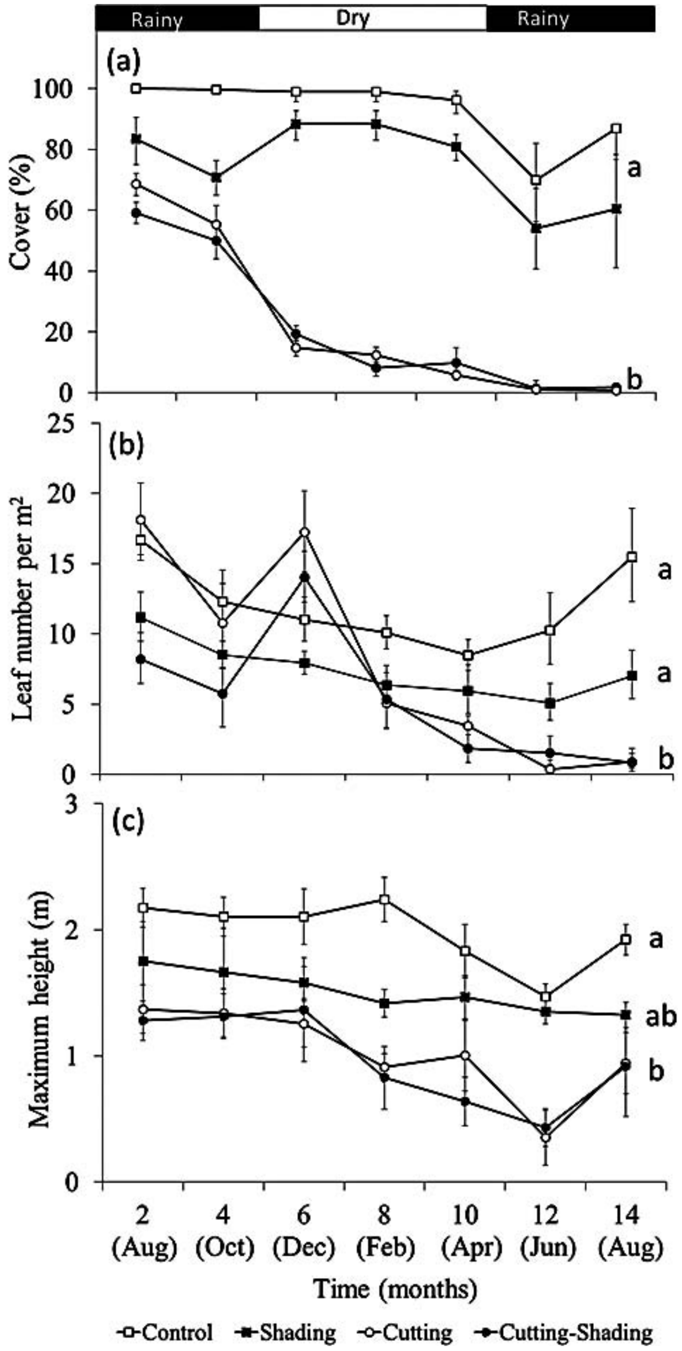

Figure 2. Response of (a) cover, (b) leaf number per m^2 and (c) maximum height of *Pteridium arachnoideum* to four treatments during 14 mo. Distinct letters indicate significant differences between treatments after 14 mo (means ± 1 SE, n = 5, $P < 0.05$). (a) and (b) show back-transformed values and (c) original data.

In all treatments, >67% of the rhizome biomass was located in the first 30 cm of soil depth (Figure 4). Rhizome

Table 1. Biomass of *Pteridium arachnoideum* and cover, biomass and richness of other plant species in August 2011 after 14 mo of treatments. Values followed by different letters within rows indicate significant differences among treatments (means ± 1 SE, $n = 5$, $P < 0.05$). External reference plots (R) had a leaf biomass of 813 ± 126 g m^{-2} and a rhizome biomass of 1074 ± 188 g m^{-2} in April 2011.

		Treatment			
		Control (X)	Shading (S)	Cutting (C)	Cutting + shading (CS)
P. arachnoideum	Leaf biomass (g m^{-2})	579 ± 99.0a	209 ± 30.5a	14.0 ± 8.3b	13.7 ± 8.2b
	Rhizome biomass (g m^{-2})	2059 ± 391a	1766 ± 234ab	1275 ± 227b	1652 ± 189ab
Other species	Cover (%)	50.6 ± 9.82a	55.5 ± 6.26a	88.0 ± 21.15ab	106.1 ± 9.38b
	Shoot biomass (g m^{-2})	94.8 ± 22.7a	86.3 ± 12.6a	154.1 ± 18.7ab	244.9 ± 28.9b
	Species m^{-2}	2.6 ± 0.40a	4.8 ± 1.16a	10.2 ± 2.08b	14.8 ± 1.53b

biomass within soil layers did not differ significantly among treatments with or without shading ($F_{[1,44]} = 0.37$, $P > 0.05$), and with or without cutting ($F_{[1,44]} = 0.23$, $P > 0.05$). However, rhizome biomass differed significantly between soil layers within treatments ($F_{[2,44]} = 49.48$, $P < 0.001$). For example, rhizome biomass was significantly higher in the soil layer of 0 to 30 cm than in 31 to 60 cm (Tukey, $P < 0.05$) in X and S treatments but not in C and CS treatments. In all treatments, there was significantly more rhizome biomass in 0 to 30 cm soil depth than in 61 to 90 cm soil depth. However, between soil layers of 31 to 60 cm and 61 to 90 cm depth, rhizome biomass did not differ in any of the treatments (Figure 4).

Completely undisturbed external reference plots (R, Figure 1) had on average 813 ± 126 g m^{-2} leaf biomass and 1074 ± 188 g m^{-2} rhizome biomass. The leaf biomass did not differ between external reference plots and control plots, but the rhizome biomass was significantly lower in external reference plots, compared to experimental control plots that had been surrounded by plastic foil (paired *t*-test, $t_9 = 3.312$, $P = 0.03$; Table 1). Therefore, plastic foil delimitation may have constrained rhizome growth expanding from control plots and consequently increased rhizome biomass within control plots.

Cost estimates for treatment methods. Annual costs of selective cutting treatments were estimated to be 840 USD ha^{-1} (Table 2). Shading costs were twice as costly for labor alone (1,680 USD ha^{-1}), and increased markedly because of the costs required to construct shade tents (18,700 USD ha^{-1}), which did not include the wooden stakes as land owners use wood from their ranches to save costs.

Succession. Both C and CS treatments resulted in significant increases in richness of other plant species

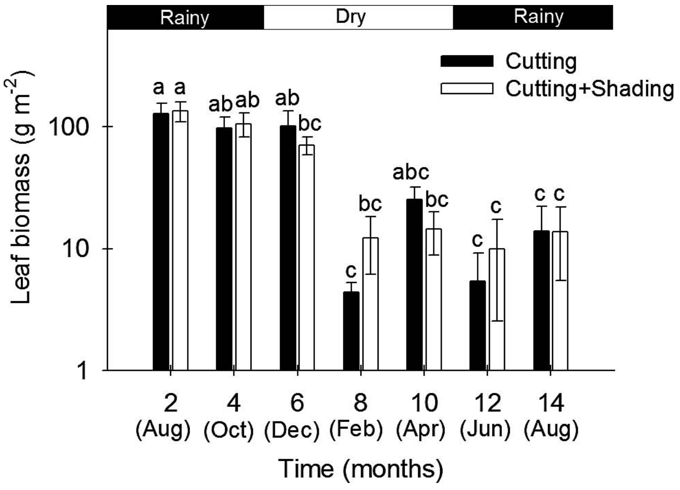

Figure 3. Dry leaf biomass of *Pteridium arachnoideum* in cutting treatments with or without shading (log scale). Bracken biomass of controls at the end of the experiment was 579 ± 99 g m^{-2}. Distinct letters indicate significant differences between treatments over time (means ± 1 SE, $n = 5$, $P < 0.05$).

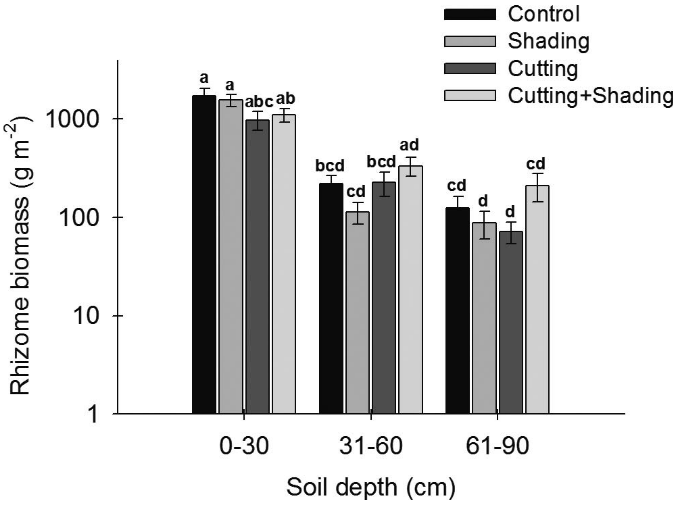

Figure 4. Dry rhizome biomass of *Pteridium arachnoideum* within the central 1 m^2 of each treatment at the end of the study (log scale). Distinct letters indicate significant differences between treatments and soil depths (means ± 1 SE, $n = 5$, $P < 0.05$).

Table 2. Estimates of annual cost per ha for different bracken management methods. All four methods require an initial nonselective cutting for 10 person-days. Shading requires the installation of shade tents. Labor costs were calculated for 8-h working days at a daily rate of 14 USD.

	Months	Selective cutting[1]	Shading[1]	Nonselective cutting	Herbicide
Labor (d)	0	10	100	10	10
	2	10	0	0	2
	4	10	0	0	0
	6	10	10	10	0
	8	10	0	0	2
	10	8	0	0	0
	12	2	10	10	0
Total labor (d)		60	120	30	14
Labor cost (USD)		840	1,680	420	196
Material costs (USD)		0	18,700	0	100
Total cost (USD)		840	20,380	420	296

[1] This study.

($F_{[1,12]} = 46.51$, $P < 0.001$), but only CS resulted in a significant increase in cover ($F_{[1,12]} = 16.83$, $p < 0.005$) and shoot biomass ($F_{[1,12]} = 17.19$, $P < 0.005$). At the end of the study, control plots had an average of 2.6 ± 0.40 species per m^2 with a mean ground cover of 50.6 ± 9.82% and shoot biomass of 94.8 ± 22.7 g m^{-2} (without bracken), whereas CS plots had a 5.7-fold increase in species richness, 2.1-fold increase of ground cover, and 2.6-fold increase of shoot biomass (Table 1). Shading alone had no significant effects on diversity, cover, or biomass of successional plant species.

Species composition differed significantly among treatments (ANOSIM2, $R = 0.419$, $P = 0.01$), and among blocks (ANOSIM2, $R = 0.592$, $P = 0.009$). In control plots, seven species persisted in the dense bracken understory. *Urochloa maxima* (Jacq.) R.D. Webster, a shade-tolerant introduced forage grass, was the only species with >5% cover (Appendix S1). In treatment plots, 32 species had newly established or had recovered vegetatively; these species were not present in control plots at the beginning of the study. Ten of these species were shared among all three treatments, and thirteen species were shared exclusively among C and CS treatments (Appendix S1). All these species were a mixture of desirable shade-tolerant grasses of secondary forests (e.g., *Dichanthelium viscidellum* [Scribn.] Gould) and shade tolerant herbs from forest edges (e.g., *Coccocypselum hirsutum* Bartl. ex DC., *Crusea calocephala* DC., *Elephantopus mollis* Kunth, and *Myrsine coriacea* [Sw.] R.Br. ex Roem. & Schult.) as well as undesirable weeds (e.g., *Rubus sapidus* Schtdl.).

Discussion

Selective Cutting and Timing of Repetitions. Our results indicate that selective cutting and removal of leaves of *P. arachnoideum* every 2 mo without shading was the most effective treatment for controlling this invasive species. Although our experiment lasted only 14 mo, seven consecutive cuttings, applied at intervals of 2 mo, effectively reduced cover of *P. arachnoideum* to <1%. Pakeman et al. (2002) reported reduced cover of *P. aquilinum* in the UK with one annual cutting to <45%. Two annual cuttings of *P. aquilinum* in Norway (Måren et al. 2008) and the U.K. (LeDuc et al. 2003; Marrs et al. 1998) and *P. arachnoideum* in Ecuador (Roos et al. 2011) reduced bracken cover to <10 to 30% of that present in control plots. The higher values of remaining cover reported in these studies suggest that cutting was not frequently enough to achieve a greater reduction in bracken cover, because it did not eliminate new emerging leaves before they had completely expanded and begun to return photosynthetic products back into the rhizome. Williams and Foley (1976) showed that emerging leaves depend completely on the reserves of the rhizome until they expand their second pair of pinnae. As such, management strategies that weaken the rhizomes are likely to be effective because these structures store starch and minerals belowground and contribute at least 60% to the total plant biomass (Lowday 1986). Land managers may have restricted their cutting treatments to save on labor costs, but longer intervals between treatments may allow rhizomes enough time to recover (Williams and Foley 1976). Cutting is a costly, labor intensive bracken management method, but six cutting treatments might be more cost effective when applied within 1 yr rather than across 3 yr, because in the first case bracken has less time to recover between treatments and provide an opportunity for other plant species to increase their ground cover. Furthermore, in frost-free tropical regions, control treatments have to be applied throughout the year to eliminate continuously emerging leaves and to achieve a comparable effect to that of two to three cuttings during the growing season in temperate regions.

The success of cutting depends on the correct timing of treatments. At our tropical study site, newly developing leaves of *P. arachnoideum* can reach up to 1.4 m in height within 2 mo, before the lamina starts to expand from the basal pinnae to the leaf apex. At this developmental stage of the leaf, the translocation of nutrients from the rhizome to the leaf is at its peak (Williams and Foley 1976). Depending on variables, such as altitude and season (Atkinson 1989), local climate, soil conditions and bracken species (Alonso-Amelot and Rodolfo-Baechler 1996), leaves may require varying time intervals for development and expansion. Consequently, the time interval between cutting and the start of laminar expansion of new leaves must be evaluated to determine adequate timing of cutting treatments at particular locations. For example, in Venezuela *P. arachnoideum* leaves expanded completely within 70 to 75 d and reached a height of ca. 124 cm (Alonso-Amelot and Rodolfo-Baechler 1996), suggesting that six cuttings per year are likely to represent a successful control strategy in that region, as at our study site in Veracruz, Mexico.

Rhizome. Although C and CS treatments were successful in reducing cover and leaf biomass of bracken, some leaves were still emerging and expanding up to a height of 1 m after 14 mo. At the end of the study, the C treatment was the only treatment that reduced mean rhizome biomass to less than 62% of that of control plots (X).

Shading also appeared to result in some positive effects on bracken, because rhizome biomass in CS treatments was not lower than that of C treatments. Shading will clearly reduce exposure to sunlight and protect bracken from photo-damaging effects of solar radiation, and may also reduce water loss during dry periods. In addition, we were unable to determine the proportion of the rhizomes that were dead or alive, so that our assessment of rhizome biomass may have underestimated the effectiveness of our treatments and reduced our ability to detect differences between treatments. Plastic foil delimitation may have caused an increase in rhizome biomass, because external reference plots (R) had a significantly lower rhizome biomass than control plots (X, Table 1) that were delimited with plastic foil. The insertion of plastic foil required the cutting of rhizomes within the first 30 cm, which is known to stimulate budding and branching of rhizomes (Robinson et al. 2010), but also may have effectively restricted rhizome growth within the experimental plot.

Although >67% of the rhizome biomass was present in the first 30 cm of soil depth, some living rhizomes with developing leaf buds were still located at 90 cm depth, perhaps because of the deep soil A horizons with similar water retention capacities reaching this soil depth (see Material and methods). Rhizomes at a depth of 1 m are well protected from fire (Hartig and Beck 2003, Le Duc et al. 2003), but surprisingly, we found signs of fire damage at 60 cm soil depth. Consequently, we assume that rhizomes of *P. arachnoideum* have not penetrated the soil to this depth, but were likely buried subsequently by decomposing bracken leaf litter that built up over the past 50 yr, after the former pasture was abandoned. The formation of deep litter layers protects bracken rhizomes against desiccation and buries seeds and young seedlings from other species (Robinson et al. 2010).

Shading. Shading alone for 14 mo had no significant effect on cover, leaf number, or leaf and rhizome biomass of *P. arachnoideum*. These results are consistent with those of Stewart et al. (2008) who reported that light shade did not increase leaf mortality and did not reduce leaf number in bracken. Consequently, emergence and expansion of new leaves were probably not limited by these light conditions. However, CS was the treatment that resulted in the greatest establishment and growth of other plant species. Shading is too costly to be applied over large areas (Table 2). Nevertheless, if reforestation rather than pasture restoration is desired, planted trees could provide shade at a lower cost than shade cloths. Trees would also be likely to compete with bracken for moisture and soil nutrients at the root level (Wilson 1988). Douterlungne et al. (2010) used large leaved, fast-growing balsa trees [*Ochroma pyramidale* (Cav. ex Lam.) Urb.] to successfully shade out bracken in Chiapas, Mexico.

Results of C and CS treatments did not differ in efficacy as much as expected, perhaps because of edge effects. Shading and control plots as well as the surrounding bracken may have incidentally shaded C treatments during the early morning and late evening hours. However, C plots were exposed to peak sun hours between 10:00 A.M. and 3:00 P.M., and the intense sunlight during this part of the day may have been the reason that the CS treatment had a higher richness of mainly shade tolerant species. In contrast, the edge effects of incidental sun-light reaching shade treatments are likely to have been negligible, because buffer zones were narrow, and only C plots with shorter vegetation may have allowed the access of direct sunlight to adjacent treatments; moreover measurements were only taken from the central 1 m^2 area in each plot (Figure 1d). Edge effects could have been reduced by choosing a larger plot size, but plots had to be small enough to repeat counting of leaf numbers and selective cutting of bracken leaves without further disturbance of experimental plots.

Succession. *Pteridium aquilinum* and other fern species, such as *Thelypteris noveboracensis* (L.) Nieuwl. and *Dennstaedtia punctilobula* (Michx.) T. Moore, may arrest succession in three ways: (1) their dense leaf canopies and thick layers of leaf litter may prevent seeds from making contact with soil

(Marrs and Watt 2006), (2) allelopathic components released from fresh or decomposing leaves may inhibit seed germination (Gliessman 1976; Hartig and Beck 2003; Silva-Matos and Belinato 2010), and (3) dense fern populations may shade out young seedlings (Royo et al. 2010). Despite these inhibitory effects, the shade tolerant *Urochloa maxima* persisted in the dense bracken understory of our control plots, and new species of desirable, mainly shade-tolerant grasses and herbs (Sierra Posada 2005) established in treatment plots quickly from newly dispersed seeds or from the seed bank. This increase of species diversity in cutting treatments was perhaps facilitated by the initial removal of all bracken leaves as well as leaf litter (Dolling 1996) and the partial elimination of allelopathic substances (Gliessman 1976). However, complete removal of leaf litter requires an additional effort that would require machinery when applied at larger scales. Future studies should compare the effect of repeated cutting with and without litter removal to evaluate the impact of litter removal alone.

Cost estimates of bracken management methods. A cost estimate of our methods in comparison to other bracken management methods indicates that herbicide application is likely to be the cheapest control method, followed by nonselective and selective cutting, which are two and four times more expensive, respectively (Table 2). However, selective cutting reduced bracken cover to less than 1%, compared to pretreatment values, whereas herbicide and nonselective cutting have been reported to reduce bracken cover to levels of 5% (Ghorbani et al. 2007) and 10 to 30% (Le Duc et al. 2003; Marrs et al. 1998; Roos et al. 2010). To evaluate the benefits of different bracken control methods, remaining cover must be correlated against gains or losses in livestock farming. However, few data are currently available to estimate the economic benefits of bracken reduction in pastures to understand how bracken cover affects the quality of pastures for livestock grazing. For instance, García-Arroyo (2013) reported that >50% of casualties of cattle in Spain, attributed to plant intoxication, were caused by *Pteridium aquilinum*. Because CS treatment did not further reduce bracken cover than cutting alone, and shading requires a relatively high economic investment, the application of shading for bracken control is unlikely to be a viable control option for farmers.

The presented cost estimates are only for the first year, but most bracken management methods, such as nonselective cutting and herbicide applications, typically require several years to be effective (Le Duc et al. 2003). Our suggested method of selective cutting may prove less expensive and more efficient than nonselective cutting or chemical control in the long term. As *P. arachnoideum* did not increase ground cover (<1%) during the final 2 mo of the experiment, it might be possible to increase cutting intervals in subsequent years and thereby reduce labor costs in a medium or long term bracken control regime based on selective cutting.

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