Creating new populations of *Acanthomintha duttonii*. II. Reintroduction at Pulgas Ridge.

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Abstract

The San Mateo thornmint, *Acanthomintha duttonii* (= *A. obovata* ssp. *duttonii*), is state and federally -listed as an endangered plant. Of the four known historical occurrences of this distinctive species in San Mateo County, California, three have been extirpated. The only remaining natural population occurs in Edgewood County Park, north of Woodside, where there is still a great potential for extinction. In order for the species to recover, populations must now be created in appropriate habitat within historic range. The current project represents the secondary phase of an effort to create the new populations and to determine the demographic, ecologic, and genetic factors that limit their growth and long-term stability. The objectives of this study included; 1) describing the demographic characteristics (size, density, survivorship, reproductive output) of the only extant natural population of *Acanthomintha duttonii* at Edgewood Park, 2) reintroducing a new population to serpentine grassland habitat at Pulgas Ridge, and 3) monitoring the demographic characteristics of the new population for comparison with the natural population at Edgewood Park.

The total population size of *Acanthomintha duttonii* (AD) at Edgewood Park increased to an estimated 18,772 plants and covered an area that was approximately 40% larger than before. However, plants were less fecund per unit of stem length than in 1990, so that nutlet production per unit of habitat area was the same as in previous, low density years. It is likely, therefore, that the natural population will stablize at its present level or even decrease in size depending on the post-dispersal fate of the new nutlet cohort. The long-term conservation significance of the newly colonized area remains to be seen. High survivorship and high fecundity indicate that the potential for continued subpopulation growth in this area is high.

The nutlets collected from Edgewood Park in 1991 for purposes of founding a new population at Pulgas Ridge had only moderate germination (63%) under optimal conditions in the laboratory. Total *in situ* germination at the Pulgas Ridge reintroduction site during the late December to early April period was low compared to these concurrent laboratory trials on the same seed lots. It averaged 25 % among 12 north-facing (NF) plots and 28 %

among 12 south-facing (SF) plots. Site aspect, therefore, had no effect on germination at Pulgas Ridge.

During the January to June growing season a total of 315 live seedlings and established plants could be found among the two sites at Pulgas Ridge, representing 27% of the total nutlets sown (1176). More plants were produced by the SF site than the NF site (166 vs. 149, respectively). Physical contact and shading among AD seedlings and other plants were rare, indicating that the effects of competition in this serpentine grassland were probably insignificant. Fewer than half of the seedlings survived to reproduce by early June. One hundred and twenty (120) AD plants, or 38% of the total plants produced during the growing season and 10% of the total nutlets sown, completed fruit formation.

Mortality began early, but its principle cause was difficult to identify. Grazing by microherbivores was the most commonly observed stress, although etiolation and wilting became more obvious in late spring. Other stresses, including pathogens, may also be important during the early phases of population growth. There were several significant differences in the patterns of mortality between NF and SF plots. Mortality rates in the NF plots were significantly higher than those in the SF plots during much of the growing season. There was significantly more stress from grazing microherbivores at NF, but other factors could have been important. Overall, survivorship to reproduction was 44 % at SF and 29 % at SF, the former being closer to the 55-59% range observed at Edgewood County Park during the same period.

Within the two subpopulations there were patterns of mortality that varied according to topographic position. At NF, mortality was lowest upslope and highest downslope near the wet bottom of the stream channel. The pattern was just the opposite at SF. This suggests that, depending on aspect, there is some favorable position along the microtopographic-moisture gradient that would minimize AD mortality. For north-facing slopes this would be approximately 2.5 to 2.8 m away from the edge of the wet channel bottom. For south-facing slopes, the favorable position would be between 0.6 and 1.0 m away from the edge. These data clearly demonstrate the very narrow habitat requirements of this endangered plant within the context of serpentine grassland.

Although the general conditions for AD reproduction at Pulgas Ridge were suitable, they were not optimal. Mean plant size at Pulgas Ridge was much less than that measured at Edgewood Park if large plants in the natural population were included from the latter estimate. If the large plants (found in a newly-colonized area) were excluded, mean plant size of the introduced population compared favorably with that of the natural population. Therefore, the large, fecund individuals observed in new, optimal habitat at Edgewood Park were missing from the Pulgas Ridge population. Perhaps optimal microhabitat patches do exist at the Pulgas Ridge reintroduction site, but they were not sown with nutlets during this experiment.

There was no difference in the sizes (and, therefore, nutlet output) of plants that grew on the NF or SF sites. Differences in subpopulation nutlet production were due only to differences in survivorship on different slope aspects. Significantly higher survivorship allowed the 72 SF plants to produce an estimated total of 691 nutlets, 103 more than were sown. The 48 NF plants produced about 466 nutlets, or 122 fewer than were sown. Therefore, the SF subpopulation has a potential for self-maintenance and perhaps growth while the NF subpopulation does not. Whether that potential can be realized after natural dispersal and *in situ* nutlet mortality at Pulgas Ridge remains to be seen.

A number of management recommendations were made, including 1) an ongoing program of demographic monitoring for the natural and reintroduced populations, including germination potential, estimates of population size, survivorship, and nutlet output 2), characterization of optimal habitat patches at Edgewood Park, combined with locating and sowing similar patches at Pulgas Ridge, 3) additional sowing of nutlets at the Pulgas Ridge site where the probablity of survival is highest - on south-facing slopes within 0.25 and 0.50 m of the ravine bottom.

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Creating new populations of *Acanthomintha duttonii*.
II. Reintroduction at Pulgas Ridge

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Introduction

The San Mateo thornmint, *Acanthomintha duttonii* (Abrams) Jokerst & B.D. Tanowitz (= *A. obovata* Jepson ssp. *duttonii* Abrams), is state and federally -listed as an endangered species. Of the four known historical occurrences of this distinctive plant in San Mateo County, California, three have been extirpated by development (York 1987, Jokerst 1991). The only remaining natural population occurs in Edgewood Park, which is administered by the San Mateo County Department of Environmental Management (Parks and Recreation Department). Although the site (see Sommers 1984 for a description) is now protected by the County, there is still a great potential for extinction. Significant changes in upslope drainage patterns have already taken place due to house and road construction. In addition, fire, vandalism (including off-road vehicles), and accidental disturbance will probably occur with increasing frequency as the adjacent human population grows.

To recover the San Mateo thornmint, the risk of extinction needs to be spread among several populations instead of being concentrated on a single population. Populations must, therefore, be created in appropriate habitat within historic range and afforded adequate protection and management (Pavlik 1993, Pavlik *et al.* 1993). The current project represents the second phase of an effort (see Pavlik and Espeland 1991) to create the new populations and to determine the demographic, ecologic, and genetic factors that limit their growth and long-term stability. The objectives of this study included; 1) describing the demographic characteristics (density, survivorship, reproductive output) of the only extant natural population of *Acanthomintha duttonii* at Edgewood Park, 2) reintroducing a new population to serpentine grassland habitat at Pulgas Ridge, and 3) monitoring the demographic characteristics of the new population for comparison with the natural population at Edgewood Park.

Methods and Materials

CHARACTERISTICS OF THE NATURAL POPULATION AT EDGEWOOD PARK

Seedling Density and Survivorship to Reproduction

Estimates of the densities of reproductive *Acanthomintha duttonii* (AD) plants at Edgewood Park (EP) were made in May 1990 and June 1991 using 0.125 m^2 circular quadrats. Five permanent quadrats were randomly positioned within the population using measuring tapes as axes and a random numbers table. These five were used to determine the mean density ($\#/m^2$) and to estimate the total size of the population when multiplied by its area (42 m^2). Eight more non-random, transient quadrats were also used to map the pattern of variation in plant density across the population.

In 1992, however, downslope expansion of the population required that two additional permanent quadrats be added. Also, the variation in plant density across the population was found to be much greater than in previous years. Areal expansion and a greater range of plant densities required that a new method be used for calculating total population size at Edgewood Park. Data from the seven permanent quadrats and from six transient quadrats were combined into a total of four mean density estimates for four different sectors of the population. Those four estimates were for the southern third (14 m^2), the middle third (14 m^2) and the northern third (14 m^2) of the 1990-91 distribution and also for the new downslope area (17 m^2). The delineation attempted to group adjacent permanent and transient plots having similar densities to obtain more homogenous estimates for each sector.

The randomly-located permanent quadrats were also used to estimate survivorship to reproduction during the 1991 and 1992 growing seasons. In 1991, 50 seedlings of AD were marked within each of five quadrats on 15 February 1991. These were revisited on 12 June and the number of marked plants still alive and flowering were tallied. In 1992, 50 seedlings of AD were marked on 4 April within each of the seven quadrats (5 old + 2 new). These were revisited on 9 June after the plants had senesced to tally the number of fruiting plants that survived to reproduce.

Plant Size and Nutlet Production

During the peak period of nutlet set in June 1992, 25 whole plants of AD were collected at EP. Each plant was cut at the soil surface and placed in its own zip-lock bag. These were returned to the lab, allowed to air dry at room temperature, and then dissected to determine 1) the total number of nutlets produced, 2) the number of glomerules, and 3) the sum of the stem lengths for each plant. Stem length was measured from the clipped point (at soil surface) to the base of the lowest glomerule. Nutlets were removed by shaking the whole plant or crushing the dry calyxes and then placed in paper envelopes. The envelopes were stored in an air-tight plastic container and refrigerated at a constant 5^{o} C. Regressions were made between nutlet output and the sum of the stem lengths per plant or the number of glomerules per plant, as in previous years (Pavlik and Espeland 1991).

All plants that survived to reproduce within the permanent quadrats were measured for stem length and number of glomerules on 15 June 1992. These were used to estimate mean plant size and nutlet output for the Edgewood Park population and to generate frequency distributions of plant size for comparison with similar data collected at Edgewood Park in May 1990 and at Pulgas Ridge in June 1992.

ESTABLISHING A NEW POPULATION AT PULGAS RIDGE

Site Selection and Microsite Evaluation

The process of selecting sites for new *Acanthomintha duttonii* (AD) populations took many factors into consideration, including the ecological (macroclimate, soil, exposure, community associates, habitat size and degree of disturbance), and the logistic (land use history, road access, property ownership). Pulgas Ridge was selected because of its high quality habitat (mesic grassland on serpentine clay soil), its public status as watershed lands operated by the San Francisco Water Department (see Appendix I), and because it is very close to, if not within, the historic range of the target species. In many ways Pulgas Ridge resembles the Edgewood Park site, although its serpentine areas are much larger and less fragmented by intrusions of non-serpentine vegetation (e.g. oaks and annual grassland). The soil at Pulgas Ridge also compared favorably with soils at Edgewood Park

Table 1. Comparison of soil samples from serpentine and non-serpentine sites occupied by members of the genus *Acanthomintha* . Serpentine sites represent existing natural population of *A. duttonii* (Edgewood) and reintroduced populations (Pulgas Ridge and Triangle). Non-serpentine sites represent natural populations of *A. lanceolata* (Iron Spring, Monterey County) and *A. illicifolia* (San Diego County) and a standard potting soil . The mean of non-serpentine soils does not include the potting soil values. SP = saturation percentage, EC = electrical conductivity (mmhos/cm), Ca and Mg in meq/l, N in % of dry weight, N, P,K, and Ni in ppm.

	SP	pH	EC	Ca	Mg	Ca/Mg	N	P	K	Ni
SERPENTINE SITES										
Edgewood	60	6.7	0.47	1.6	2.4	0.667	0.074	9.5	309.0	26.9
Pulgas Ridge	73	6.6	0.45	1.2	2.4	0.500	0.074	5.1	205.0	37.0
Triangle	76	7.4	0.93	2.0	6.8	0.294	0.086	7.6	74.0	39.4
mean ± S.D.	70 ± 7	7.1 ± 0.4	0.62 ± .022	1.6 ± 0.4	3.9 ± 2.5	0.487 ± .187	0.078 ± .007	7.4 ± 2.2	196 ±117	34.4 ± 6.6
NON-SERPENTINE SITES										
lanceolata	24	7.2	0.64	3.2	2.4	1.333	0.069	13.1	160.0	4.5
illicifolia	60	7.3	0.63	2.8	2.0	1.400	0.052	7.4	338.0	1.8
potting soil	200	6.7	1.56	7.6	6.0	1.267	0.190	200.0	400.0	8.4
mean ± S.D.	42 ±18	7.2 ± 0.1	0.63 ± 0.01	3.0 ± 0.3	2.2 ± 0.3	1.367 ± .047	0.061 ± .012	10.2 ± 4.0	249 ±126	3.2±1.9

(Table 1) because it is rich in clay (high saturation percentage) and chemically typical of serpentine (low nitrogen, low calcium/magnesium ratio, high nickel). The Triangle site, located near the western margin of Edgewood Park, also had favorable characteristics and should be considered for additional AD reintroduction projects (also see McCarten 1986).

The exact location of the reintroduction (the microsite, Figure 1) was determined from field and laboratory studies conducted during 1990-1991 (Pavlik and Espeland 1991). In addition to the ecological and logistic criteria discussed above, the microsite was selected to be; 1) large enough to allow a total of 24, 26 X 28 cm quadrats, separated by row and column spaces (access paths), 2) relatively homogeneous with respect to microhabitat factors (soil depth, slope, associated species, etc.), 3) accessible but reasonably concealed to reduce the potential for vandalism or other human disturbance, and 4) surrounded by suitable habitat so as not to constrain population growth in the future. We chose an east-west trending channel of a small intermittent stream, with gently-sloping (25%) banks of serpentine clay.

The north and south-facing banks of the channel allowed us to test the importance of aspect by installing two subpopulations; one on the north-facing bank and one on the south-facing bank. Furthermore, the topographic position of the plots on each bank would be along a soil moisture gradient (Figure 2): plots towards the bottom of the bank would be wetter than those near the top of the bank (total elevation change of about 1 m over a distance of about 4 m). This was reflected in the vegetation patterns, with sparse *Juncus* in some parts of the stream channel transitioning to *Stipa pulchra* and a rich assemblage of native herbs on the banks. Other than aspect, however, the two slopes were identical. Plant cover was relatively sparse and open and would not excessively shade or otherwise crowd the new AD plants. The site was not fenced to avoid attracting people to the site.

Characteristics of the Founder Nutlets

All of the propagules (= nutlets) of *Acanthomintha duttonii* used in this reintroduction were collected from Edgewood Park in May of 1990 and June of 1991. Nutlets were taken from at least 40 individuals that represented the complete size range and microenvironmental amplitude of the natural population. The collection would be likely, therefore, to contain a representative sample of the existing genetic variation (Falk and Holsinger 1992). Nutlets were stored at 4^{o} C in paper pouches within sealed plastic bags until they were sown in the field.

Laboratory germination trials were conducted using the 1990 and 1991 collections, the results of which were reported earlier (Pavlik and Espeland 1991). In order to estimate the maximum number of germinules that could arise at Pulgas Ridge, another set of laboratory germination trials was conducted in January 1992 using three replicates of 25 nutlets each. A replicate consisted of a plastic petri dish (5.5 cm diameter) containing a filter paper disk that was kept moist with distilled water. Nutlets were spread across the paper disks and kept in a dark room in which the temperature averaged 25 C. Replicates were checked every day for 12 days, noting germination (protrusion of the radicle through the pericarp) and removing germinules with a soft paintbrush.

Installation of the New Population

Each of the two subpopulations (north-facing or NF, south-facing or SF) was installed by using 12 precision-sown plots arranged in a cross formation (Figure 2), with 0.20 m strips separating adjacent plots. The locations of the plots were permanently marked with two, 20 cm long wooden rods driven into the soil so that 5 cm protruded above the surface. The rods positioned a removable wooden frame, 18 x 18 cm, into which a grid of 49 holes (7 holes x 7 holes, each 2.5 cm diameter) had been drilled. The holes allowed exact placement of nutlets within the plot and subsequent monitoring of germinules and juvenile plants. This technique has been successfully used by Pavlik et al. (1993a,b) to establish and monitor new subpopulations of the endangered *Oenothera deltoides* ssp. *howellii* and *Erysimum capitatum* var. *angustatum* at Antioch Dunes National Wildlife Refuge and by Pavlik (1990, 1991) to establish and monitor new populations of *Amsinckia grandiflora* .

A total of 1,176 nutlets of *Acanthomintha duttonii* , half from the 1990 crop at Edgewood and half from the 1991 crop, were sown on 9 September 1991 into the 24 plots at Pulgas Ridge. After a frame was in place, a blunt nail was used to drill 1 cm deep depressions into the mineral soil beneath each sowing hole. One nutlet was pressed into each depression (49 per plot) and covered with about 20 cc of loose, native soil. The 1990 and 1991 sources were mixed so it was not possible to follow the fates of germinules produced from different cohorts. No supplements of water or nutrients were applied during the experiment, even though the site received only 75 % of its average precipitation during the 1 October to 1 May rainy season.

Monitoring and Evaluation

The fate of each nutlet was followed during the January to June growing season by repositioning the wooden frames on each plot and searching for seedlings. The condition of each seedling was recorded on plot-specific data sheets to allow calculation of critical demographic parameters (Pavlik 1993). Those parameters included field germination, stress factors (desiccation, etiolation, grazing by microherbivores), mortality, phenology, reproductive survivorship, and plant size (number of glomerules and stem length). All plots were censused on 28 January, 10 March, 8 April, 14 May, and 9 June 1992.

To estimate nutlet production of the new Pulgas Ridge population, the relationship between plant size and nutlet output developed for the 1992 Edgewood Park population (see above). Combined with plant size measurements from Pulgas Ridge, the equation would estimate nutlet output for each plant in the new population. This allowed a non-destructive assessment of reproductive performance *in situ* and comparisons with plants from the natural population.

Results and Discussion

CHARACTERISTICS OF THE NATURAL POPULATION AT EDGEWOOD PARK

Seedling Density and Survivorship to Reproduction

The population of *A. duttonii* at Edgewood Park covered an area of about 42 m^2 in 1990 and 1991, with densities ranging from 64 plants/m^2 to 960 plants/m^2 during the reproductive months of May and June (Figure 3). Relative large amounts of variation were found in 1990 compared to 1991, which had ranges of 896 plants/m^2 and 352 plants/m^2 across the population (Table 2).

During 1992, the population expanded downslope and towards the north by approximately 4.4 m and covered a total of 59 m^2 of serpentine clay habitat. Because signs of upslope erosion and downslope deposition were visible in early April, nutlets were probably carried by storm runoff into a previously unoccupied area. It is unclear whether the runoff was unusually strong because of rainfall intensity or because of changes in upslope drainage from local residential development. Nevertheless, colonizing plants grew quite well, especially where the soil appeared dry on its surface early in the sping.

Across the old and new areas, AD densities had a much greater variation in 1992 than in previous years, from 8 plants/m^2 to 1736 plants/m^2 (range of 1726 plants/m^2). Low densities occurred in the new downslope sector and in the upslope, southern sector of the population. The highest densities were found in the center of the population, near what was once the northern border of the distribution. Using the values of mean density from the four sectors, the total reproductive population was estimated to be 18,772 individuals in June 1992.

Survivorship to reproduction was relatively high and similar in 1991 and 1992, with 55 - 59% of the plants recorded in early spring present as flowering individuals in June. There was, however, large variation across the population in 1992 that formed a distinctive spatial cline (Figure 4). Survivorship was very low in the southern sector and progressively increased going downhill and towards the north. Plants in the new area had 90-100%

Table 2. Density and survivorship of *Acanthomintha duttonii* at Edgewood Park, 1990 to 1992. n = 5 permanent quadrats for 1990 and 1991, n = 7 for 1992 overall. Density and survivorship in 1992 also shown by sector. na = data not available

year	mean density (# plants/m^2)	range of density (# plants/m^2)	mean survivorship (%)	estimated total repro population size
1990	302 ± 294	64 - 960	na	12,864
1991	230 ± 78	80 - 432	54.8 ± 14.9	9,660
1992 - overall	689 ± 704	8 -1736	59.4 ± 29.4	18,772
south	44 ± 4	40 - 48	6.0	616
middle	324 ± 44	268 - 376	42.0	4,536
north	934 ± 595	108 -1736	59.3 ± 10.0	13,076
new	32 ± 24	8 - 56	95.0 ± 5.0	544

survivorship even though they were at densities similar to those in the southern sector which had very low (6%) survivorship. Where plant densities were the highest, survivorship was still in the 46-70% range. Thus, the patterns of AD survivorship in 1992 were not strictly density-dependent. Instead, changes in the spatial distribution of critical habitat factors (moisture, clay, soil fissures) have shifted the distribution of the population. The long-term significance of those redistributions, however, remains obscure.

Plant Size and Nutlet Production *in situ*

The output of nutlets by *Acanthomintha duttonii* plants at Edgewood Park was linearly related to the sum of the stem lengths per plant (Table 3, Figure 5). Although the slopes of the relationships were similar in 1990 and 1992, the intercepts were not. The number of glomerules per plant was also positively correlated with nutlet output (Table 3, Figure 6), but with very little difference in slopes and intercepts between years. These results indicate that plants in 1992 had to be larger than plants in 1990 to produce the same number of glomerules. Or, put another way, 1992 plants produced fewer glomerules per cm of stem length because resources were allocated to vegetative growth (above and/or below-ground) rather than to reproduction.

Most plants at EP fell into the one glomerule or short stem length categories, and there were relatively few large plants in the population (Figure 7). This suggests that habitat conditions were sub-optimal in 1992, either because of rainfall and temperature patterns and/or because of high seedling density and intraspecific competition. However, comparing the 1992 frequency distributions with the 1990 frequency distributions (Figure 8) shows that more large plants were produced in 1992 than in 1990. Mean plant size (total stem length) in 1992 was 6.9 ± 7.1 cm while in 1990 it was 4.7 ± 2.5 cm. The larger size and greater variance in 1992 was due mainly to the presence of a few robust plants (> 18 cm stem length and > 5 glomerules) in the newly-colonized area. Otherwise, mean plant size would have been the same in 1992 and 1990 (4.0 ± 2.9 cm and 4.7 ± 2.5 cm, respectively) and the frequency distributions would be similarly skewed towards small individuals with short stems (2-6 cm) and few (1-2) glomerules. Colonization of the new area downslope, therefore, provided quality habitat that favored more robust growth and higher nutlet output of AD plants.

Using the 1992 values of mean plant density (689 pl/m^2) and mean plant size (6.9 cm of stem length), combined with the 1992 nutlet output equation (Table 3), a rough estimate of nutlet production can be obtained. An average of 11,024 nutlets/m^2 were produced in 1992 at EP, compared to 10,363 nutlets/m^2 in 1990 (using the appropriate 1990 data and equation). The similarity in these estimates indicates that higher plant densities in 1992 resulted in lower fecundity through intraspecific competition. Indeed, if the large colonist plants were excluded from the calculations, the 1992 estimate of nutlet rain would drop to 7,372 nutlets/m^2 and indicate a decline in the size of next year's population. Such density-dependent regulation of population growth is well documented in annual species, including those which are widespread and abundant (see Harper 1977). Continuing dispersal throughout the new favorable habitat, however, could compensate for reductions in the size of the main population if conditions remain favorable during the next few years.

Table 3. Linear correlations between various measures of plant size and nutlet output per *Acanthomintha duttonii* individual, May 1990 and June 1992.

n	X	Y	slope	intercept	r	P
Edgewood Park 1992						
25	# glomerules/plant	# nutlets	13.16	-2.84	.91	<0.01
25	Σ of stem lengths (cm)	# nutlets	1.88	3.09	.85	<0.01
Edgewood Park 1990						
40	#glomerules/plant	#nutlets	12.68	11.72	.80	<0.01
40	Σ of stem lengths (cm)	# nutlets	2.83	21.11	.71	<0.01

ESTABLISHING A NEW POPULATION AT PULGAS RIDGE

Laboratory Germination of the Founding Nutlets

When tested in January 1992, founder nutlets from the 1991 crop had only moderate rates of germination in the laboratory. Germination averaged 63% for 1991 nutlets, compared to 87% for 1990 nutlets (tested in April 1991), even though both crops were approximately one year old at the time the tests were conducted. This 25% difference in germination potential could be due to deleterious genetic and environment factors that operate in small populations (Menges 1991). Such factors are of importance when creating new populations because germination in the field would be further reduced by patchiness in the soil environment, poor nutlet-soil contact, and nutlet death due to predation or disease (Pavlik et al. 1993a,b, Pavlik and Espeland 1991). As a result, the founding population at Pulgas Ridge would probably be smaller than predicted when the reintroduction was designed and less likely to to exhibit robust demographic characteristics.

Field Germination

Although the first winter storm of 1991-92 dropped more than 50 mm of precipitation over a two day period in late October, germination of *A. duttonii* was delayed until the next major storm. That storm came between 27 and 30 December, bringing 59 mm to the nearby station at Redwood City. Late winter germination appears to be characteristic of this species, owing to a rigid endogenous control mechanism that stratification, pericarp scarification, fire, wet-dry cycling and red light cannot override (Pavlik and Espeland 1991). Perhaps such a mechanism prevents germination before a thorough saturation of the clay substrate takes place, thus avoiding the possibility of seedling desiccation during warm days in fall and early winter. Percolation is slower within clay substrates and so a higher proportion of the falling rain is likely to run off. Furthermore, clay particles require much more water than sands and gravels to bring soil water potentials into the tolerable range of -0.1 to -1.5 MPa for most seedlings.

Total *in situ* germination (% of nutlets sown) during the late December to early April period was low compared to concurrent laboratory germination on the same seed lots. Among all 12 north-facing (NF) plots, it averaged 25.3 ± 10.4 %, with a high of 46.9 % in plot 3. This was statistically identical to the 28.2 ± 12.1 % total germination found among the south-facing (SF) plots where the high was 53.1 % in plot 5. Site aspect, therefore, had no effect on total germination at Pulgas Ridge.

The temporal pattern of germination was similar but statistically distinct between the two sites. Overall, most germination took place by 28 January 1992, with 73% of the total germination for the year recorded since the triggering rainfall event one month earlier. All seedlings were in the cotyledon stage during this first complete census. The soil was quite saturated at both the NF and SF sites, but firmer under foot at the latter. An additional 22% of the total germination occurred between 28 January and 10 March, with the remaining 5% between 10 March and 8 April. No germination was recorded after the April census in any of the plots. Despite sharing this overall pattern, the NF and SF sites were distinctive. Germination responded more quickly in the NF plots, with 79.6 ± 12.3 % recorded by 28 January, compared to 66.2 ± 12.4 % in the SF plots ($F = 6.05$, 1/22 df, $P<0.025$, ANOVA). This dropped off more rapidly to 16.1 ± 9.5 % in the NF plots , whereas it was sustained at a higher level (26.9 ± 11.7 %) in the SF plots during the spring ($F = 5.57$, 1/22 df, $P < 0.05$). These differences probably did not have a large impact on the dynamics of the Pulgas Ridge population, but instead reflected microenvironmental differences in soil moisture and exposure between the two slopes.

Seedling Establishment and Mortality

During the January to June growing season a total of 315 live seedlings and established plants could be found among the two sites at Pulgas Ridge, representing 27% of the total nutlets sown (1176). More plants were produced by the SF site than the NF site (166 vs. 149, respectively), but mean number of plants per plot were the same for the two subpopulations (13.8 ± 5.9 vs. 12.4 ± 5.1, respectively). In a larger population these plot densities would correspond to densities if 176 and 158 plants/m^2, respectively, both falling with the range observed in the natural population at Edgewood Park (Table 2). Physical contact and shading between the AD seedlings and other plants were rare because of the 1) virtual absence of annual grasses, 2) relatively large spaces between *Stipa pulchra* bunches and 3) the open or lax growth forms of the common herbs (e.g. *Perideridia kelloggii, Delphinium virgatum*) in this serpentine grassland.

Despite the moderate production of seedlings at Pulgas Ridge, fewer than half survived to reproduce by early June. Only 120 AD plants completed fruit formation, or 38% of the total plants produced during the growing season and 10% of the total nutlets sown. Mortality began early, with weekly mortality rates as high as 16.9% per week during the 28 January to 10 March period. The principle cause was difficult to identify from observations of grazing, desiccation, and etiolation stresses. Grazing by microherbivores (insects, snails, etc.) was the most commonly observed stress, affecting 4-34% of all live plants during the growing season. The loss of whole shoots, leaves and cotyledons was rarely noted, and the amount of tissue missing from any one plant was usually small. Wilting of plants occurred in April and May, but on the whole it affected only 3-10% of all live plants. Likewise, etiolation was observed in less than 3% of all live plants, except during May when 20-30% of the population was affected (perhaps as nutrients were reallocated to flower and fruit production). Other stresses, including pathogens, may also be important during the early phases of population growth, but these were not assessed during this study.

There were several significant differences in the patterns of mortality between NF and SF plots and even within those plots along the topographic-moisture gradient. Mortality rates in the NF plots were significantly ($P< 0.025$) higher than those in the SF plots during the January-March and March-April periods (Figure 9). This was the primary reason for differences in the shapes of the subpopulation growth curves (Figure 10). Growth of the SF subpopulation is best described by a parabola ($y = 11.56 + 3.15x - 1.80^{-2}x^2$, $r^2 = 0.95$) that peaked in early April prior to flower formation. Its shape was the result of germination in the early months and mortality during reproduction. Growth of the NF subpopulation, however, is best described by a fifth order polynomial ($y = 1.15 + 8.10x - 0.19x^2 + 1.60^{-3}x^3 - 4.44^{-6}x^4$, $r^2 = 0.97$) that reflects high mortality during seedling establishment as well as reproduction. There was significantly more stress from grazing microherbivores at NF during the March to April period (34% of SF plants vs. 14% of NF plants affected, ANOVA $P < 0.05$), but other factors could have also been important. Although mortality rates were low between April and May, they increased abruptly as flowering and fruiting occurred in May and June. Mortality in the SF plots was significantly higher ($P < 0.05$) than in the NF plots at that time. Many more SF plants were visibly etiolated (31% of SF vs. 5% of NF live plants, ANOVA $P < 0.001$), but wilting was equally uncommon on both sites. Overall, survivorship to reproduction was 44.2 ± 14.4% at SF and 29.1 ± 16.4 at SF, the former being closer to the 55-59% range observed at Edgewood Park.

Within the two subpopulations there were patterns of mortality that varied according to topographic position. At NF, mortality was lowest upslope and highest downslope near the wet bottom of the stream channel (Figure 11). The pattern was just the opposite at SF. This suggests that, depending on aspect, there is some favorable position along the microtopographic-moisture gradient that would minimize AD mortality. For north-facing slopes this would be at topographic positions 1 or 2, approximately 2.5 to 2.8 m away from the edge of the wet channel bottom, perhaps to avoid moist conditions that favor microherbivore activity or attack by pathogens. For south-facing slopes, the favorable position would be between 0.6 and 1.0 m away from the edge so that more moisture would be available to compensate for exposure to higher temperatures. These reasons are quite speculative, but the data clearly demonstrate the very narrow habitat requirements of this endangered plant within the context of serpentine grassland.

Plant Size and Nutlet Production

Mean plant size at Pulgas Ridge was much less than that measured at Edgewood Park (3.5 ± 1.5 cm vs. 6.9 ± 7.09 cm), but only if the large colonizing plants of the natural population were included in the latter estimate. By excluding the colonists, mean plant size of the introduced population compared favorably with that of the natural population (3.5 cm vs. 4.0 cm, respectively). This is also true for comparisons of the plant size frequency distributions (Figures 12 and 7): in both the introduced and natural populations of 1992, the most common stem length category was 2-4 cm and the most common number of glomerules was 1. Missing from the Pulgas Ridge population were the large, fecund individuals observed primarily as colonists in the new area at Edgewood Park. This indicates that although the general conditions for AD reproduction at Pulgas Ridge were suitable, they were not optimal. Perhaps optimal microhabitat patches do exist at the Pulgas Ridge reintroduction site, but they were not sown with nutlets during this experiment. Such patches can have a disproportional effect on population growth by producing a few, highly fecund individuals that generate hundreds, rather than tens, of nutlets each. Characterizing, locating and sowing those optimal patches should be the next recovery objective at Pulgas Ridge.

There was no differences in the sizes (and, therefore, the nutlet output) of plants that grew on the NF or SF sites. Mean stem length for NF plants was 3.5 ± 1.6 compared to 3.4 ± 1.5 for SF plants and their frequency distributions were similar (Figure 13). Differences in subpopulation nutlet production, therefore, were due only to differences in survivorship on different slope aspects. Significantly higher survivorship allowed the 72 SF plants to produce an estimated total of 691 nutlets, 103 more than were sown. The 48 NF plants produced about 466 nutlets, or 122 fewer than were sown. Therefore, the SF subpopulation has a potential for self-maintenance and perhaps growth while the NF subpopulation does not. Whether that potential can be realized after natural dispersal and *in situ* nutlet mortality at Pulgas Ridge remains to be seen.

Conclusions and Management Recommendations

1) The total population size of *Acanthomintha duttonii* at Edgewood Park increased to 18,772 plants and covered an area that was approximately 40% larger than in previous years. High survivorship to reproduction (mean of 59%), especially in the newly colonized area, resulted in high plant densities in some sectors of the population. However, plants were less fecund per unit of stem length than in 1990, so that average nutlet production per unit of habitat area was the same as in previous, low density years. It is likely, therefore, that the original population (occupying the 1990-1991 area) will stablize at its present level or even decrease in size depending on the post-dispersal fate of the new nutlet cohort.

An ongoing program of demographic monitoring, including estimates of population size, survivorship, and nutlet output is recommended. These data allow analysis of trends in the only natural population of this distinctive, highly endangered species and provide a basis for evaluating the performance of reintroduced populations created for purposes of recovery.

2) The long-term conservation significance of the newly colonized area remains to be seen. High survivorship and high fecundity indicate that the potential for continued subpopulation growth in this area is high. If the colonists successfully re-establish themselves, then the storm events that initially disrupted the Edgewood Park population may have produced the beneficial effect of dispersing nutlets into a previously unoccupied and appropriate habitat.

An ongoing program of demographic monitoring, including estimates of population size, survivorship, and nutlet output is recommended in order to evaluate trends within the new subpopulation.

3) The nutlets collected from Edgewood Park in 1991 for purposes of founding a new population at Pulgas Ridge had only moderate germination in the laboratory. Compared to nutlets collected in 1990, there was a 25% decline in maximum germination for no apparent reason. Decreases in germination potential can be due to deleterious genetic and environment factors that operate in small populations.

For these reasons, ongoing evaluation of nutlet cohorts is required to determine the conservation significance of declining germination potential in the Edgewood Park population.

4) Total *in situ* germination (% of nutlets sown) at the Pulgas Ridge reintroduction site during the late December to early April period was low compared to concurrent laboratory germination trials on the same seed lots. It averaged 25.3 ± 10.4 % among all 12 north-facing (NF) plots and 28.2 ± 12.1 % among the 12 south-facing (SF) plots. Site aspect, therefore, had no effect on total germination at Pulgas Ridge. Most germination took place by 28 January 1992, with 73% of the total germination for the year recorded since the triggering rainfall event one month earlier. Germination responded more quickly in the NF plots, but the difference probably did not have an impact on the dynamics of the Pulgas Ridge population.

5) During the January to June growing season a total of 315 live seedlings and established plants could be found among the two sites at Pulgas Ridge, representing 27% of the total nutlets sown (1176). More plants were produced by the SF site than the NF site (166 vs. 149, respectively), but mean number of plants per plot were the same for the two subpopulations (13.8 ± 5.9 vs. 12.4 ± 5.1, respectively). Physical contact and shading between AD seedlings and other plants were rare, indicating the the effects of competition in this serpentine grassland were probably insignificant. Fewer than half of the seedlings survived to reproduce by early June. Only 120 AD plants completed fruit formation, or 38% of the total plants produced during the growing season and 10% of the total nutlets sown.

6) Mortality began early, but its principle cause was difficult to identify. Grazing by microherbivores was the most commonly observed stress, although etiolation and wilting became more obvious in late spring. Other stresses, including pathogens, may also be important during the early phases of population growth. There were several significant differences in the patterns of mortality between NF and SF plots. Mortality rates in the NF

plots were significantly (P< 0.025) higher than those in the SF plots during much of the growing season. There was significantly more stress from grazing microherbivores at NF, but other factors could have also been important. Overall, survivorship to reproduction was 44.2 ± 14.4% at SF and 29.1 ± 16.4 at SF, the former being closer to the 55-59% range observed at Edgewood Park. Within the two subpopulations there were patterns of mortality that varied according to topographic position. At NF, mortality was lowest upslope and highest downslope near the wet bottom of the stream channel. The pattern was just the opposite at SF. This suggests that, depending on aspect, there is some favorable position along the microtopographic-moisture gradient that would minimize AD mortality. For north-facing slopes this would be at topographic positions 1 or 2, approximately 2.5 to 2.8 m away from the edge of the wet channel bottom. For south-facing slopes, the favorable position would be between 0.6 and 1.0 m away from the edge. These data clearly demonstrate the very narrow habitat requirements of this endangered plant within the context of serpentine grassland.

Additional sowing of nutlets at the Pulgas Ridge site should occur where the probablity of survival is highest - on south-facing slopes between 0.6 and 1.0 m away from the edge of the channel bottom.

7) Although the general conditions for AD reproduction at Pulgas Ridge were suitable, they were not optimal. Mean plant size at Pulgas Ridge was much less than that measured at Edgewood Park (3.5 ± 1.5 cm vs. 6.9 ± 7.09 cm) if the large colonizing plants of the natural population were included in the latter estimate. By excluding the colonists, mean plant size of the introduced population compared favorably with that of the natural population (3.5 cm vs. 4.0 cm, respectively). Therefore, the large, fecund individuals observed in new, optimal habitat at Edgewood Park were missing from the Pulgas Ridge population. Perhaps optimal microhabitat patches do exist at the Pulgas Ridge reintroduction site, but they were not sown with nutlets during this experiment.

Characterizing optimal habitat patches at Edgewood Park, combined with locating and sowing similar patches at Pulgas Ridge should be the next recovery objective for enhancing this reintroduced population of *Acanthomintha duttonii*.

8) There was no difference in the sizes (and, therefore, nutlet output) of plants that grew on the NF or SF sites. Differences in subpopulation nutlet production were due only to differences in survivorship on different slope aspects. Significantly higher survivorship

allowed the 72 SF plants to produce an estimated total of 691 nutlets, 103 more than were sown. The 48 NF plants produced about 466 nutlets, or 122 fewer than were sown. Therefore, the SF subpopulation has a potential for self-maintenance and perhaps growth while the NF subpopulation does not. Whether that potential can be realized after natural dispersal and *in situ* nutlet mortality at Pulgas Ridge remains to be seen.

An ongoing program of demographic monitoring, including estimates of population size, survivorship, and nutlet output is recommended for the reintroduced population at Pulgas Ridge. These data provide a basis for evaluating the population performance for purposes of recovery. Given the availability of nutlets from the 1992 population and the generally favorable performance of plants on the south-facing slope, additional precision sowing is recommended for Pulgas Ridge during the 1992-1993 season.

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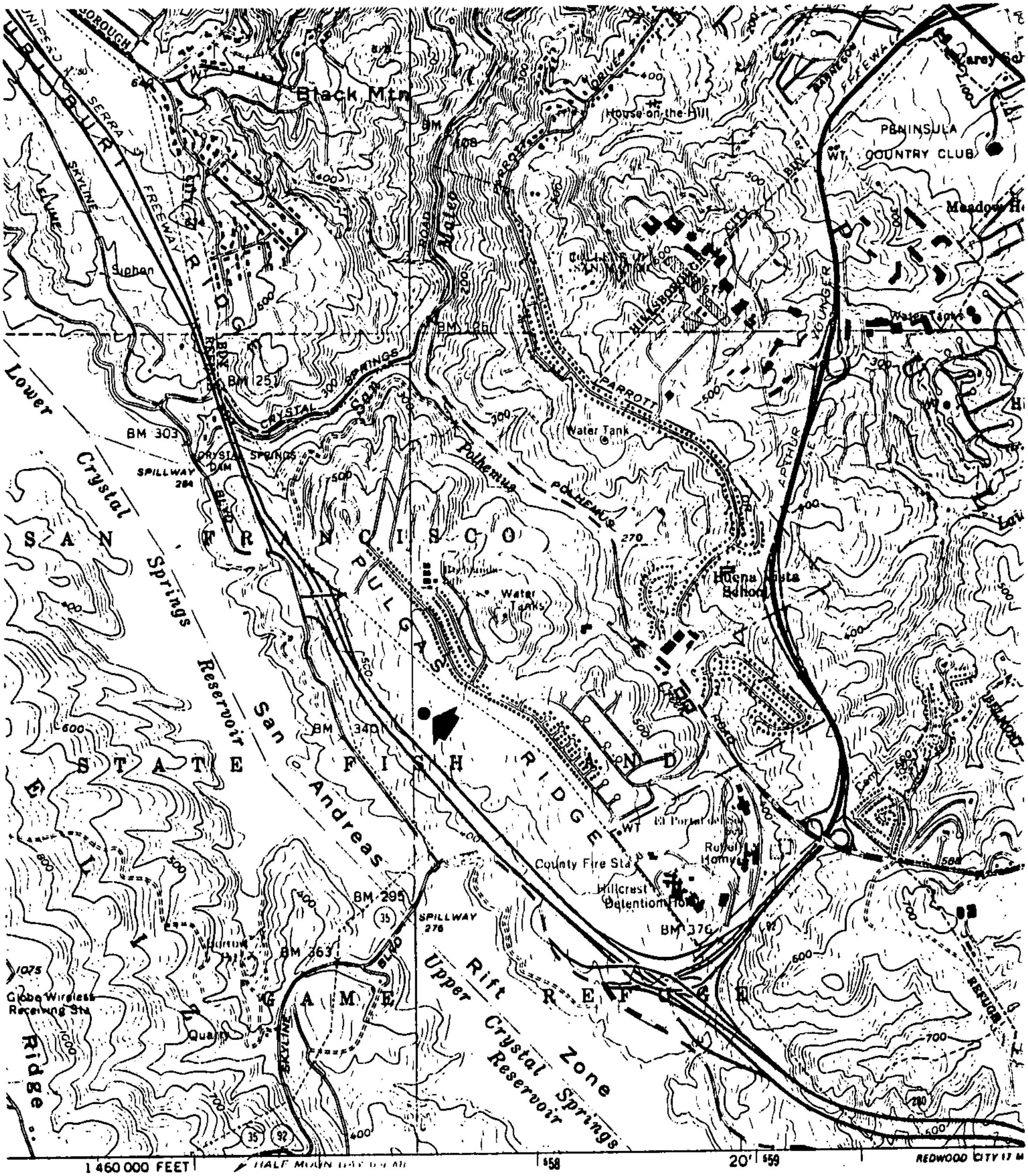


Figure 1. Location of the reintroduction site for <u>Acanthomintha duttonii</u> on Pulgas Ridge. From the U.S.G.S. 7.5' San Mateo quadrangle.

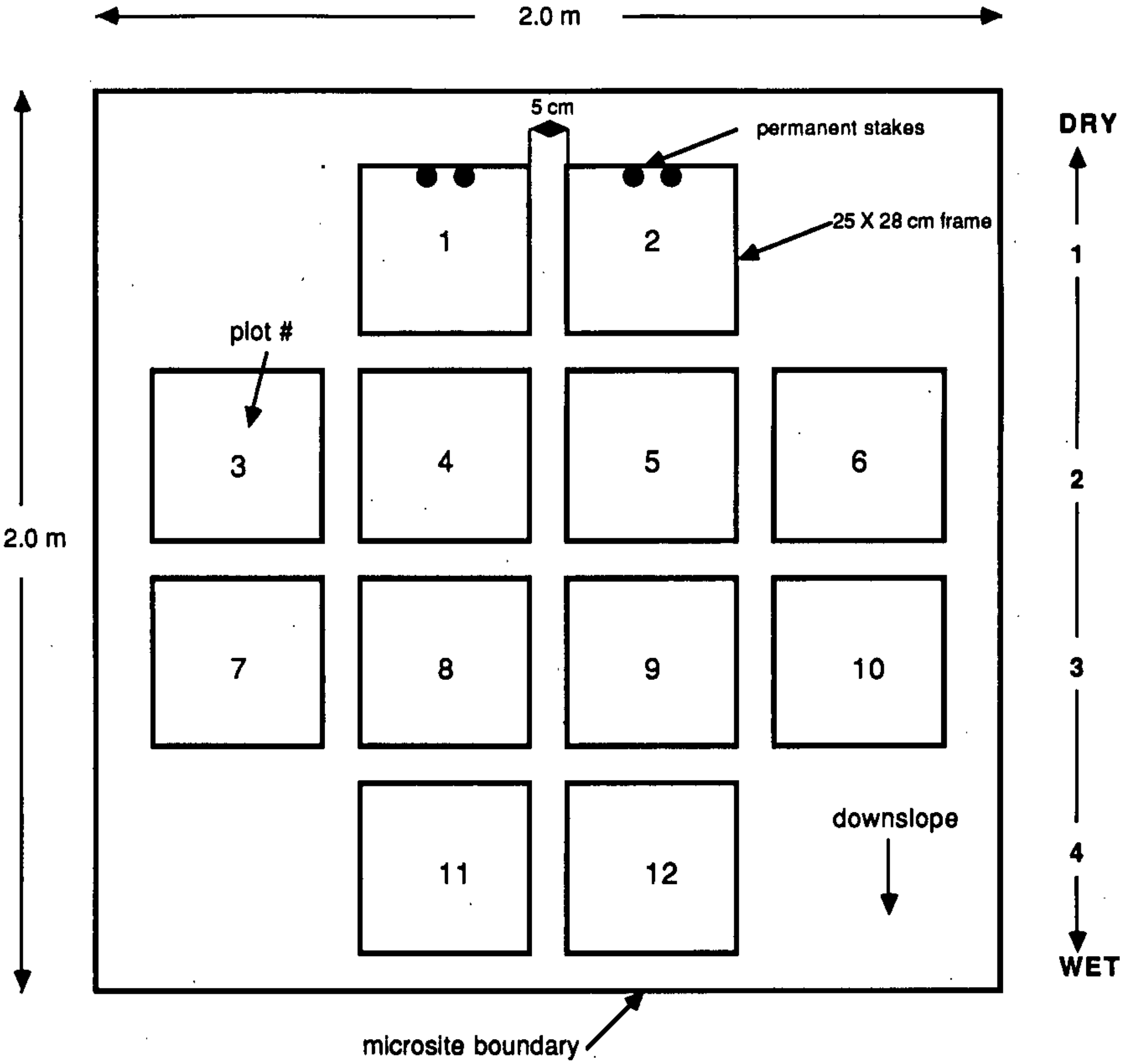


Figure 2. Plot layout for A. duttonii reintroduction along a topographic-moisture gradient. Downslope microsite boundary was approximately 0.5 m away from the edge of the stream bed. One set of 12 plots was used for each slope aspect (north-facing or south-facing).

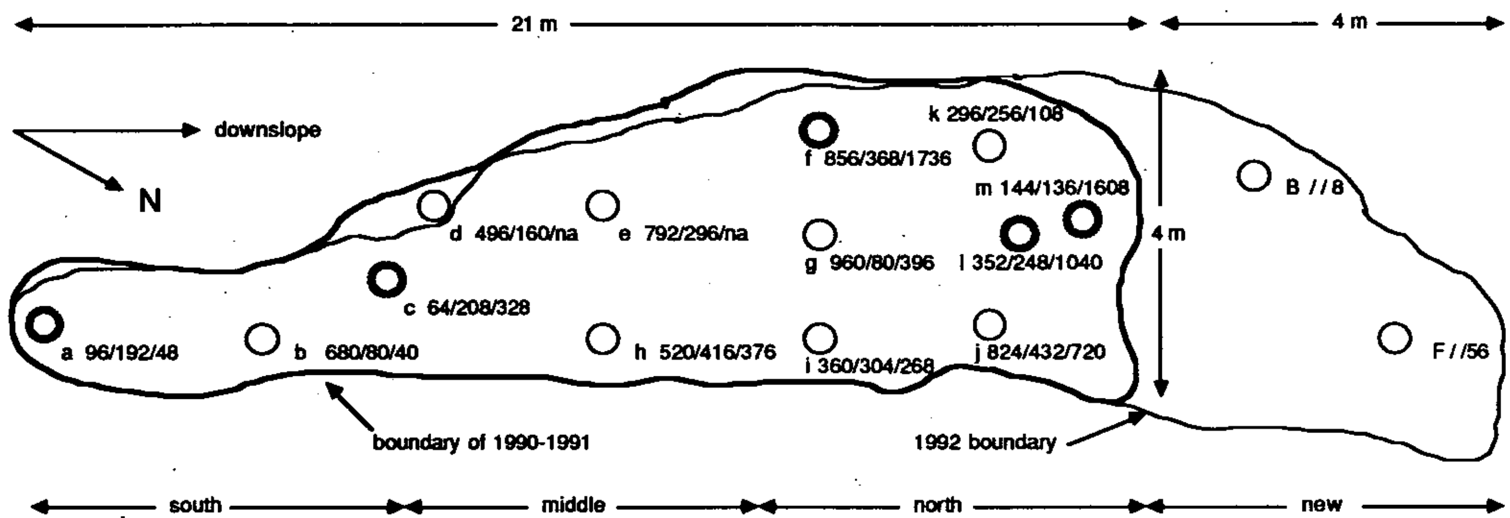


Figure 3. Density (# plants/m^2) of A. duttonii for 1990/1991/1992 at Edgewood Park. Old and new (thin line) population boundaries shown.

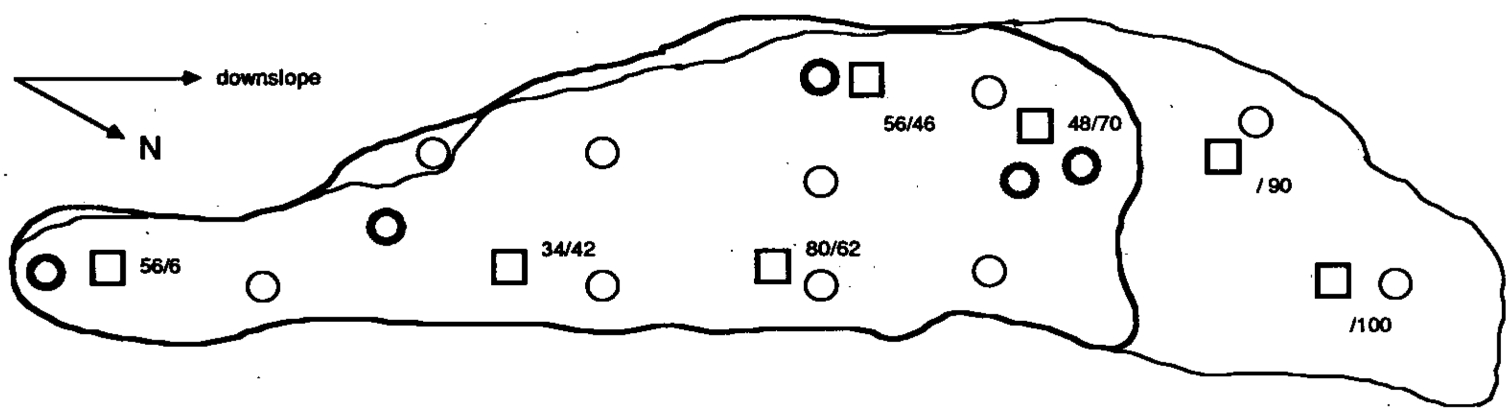


Figure 4. Survivorship (%) of A. duttonii within 1991/1992 plots at Edgewood Park.

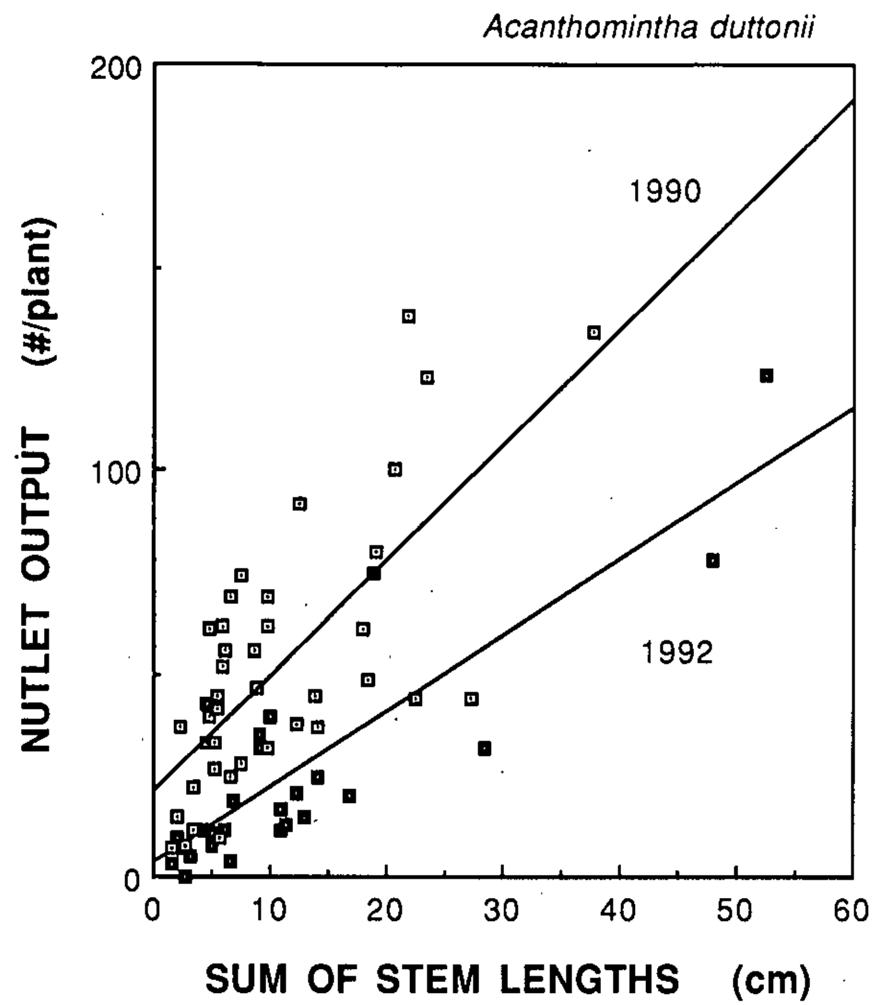


Figure 5. Nutlet output as a function of stem length of plants at Edgewood Park, 1990 and 1992. See Table 3 for line Equations.

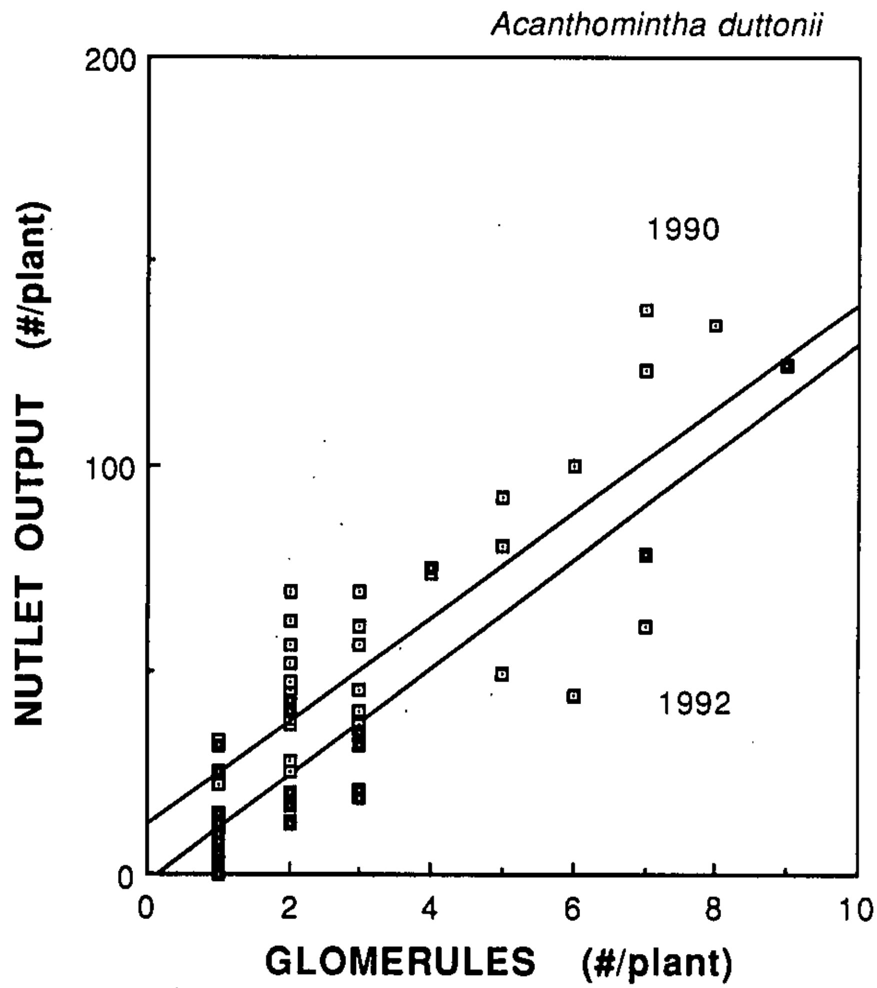
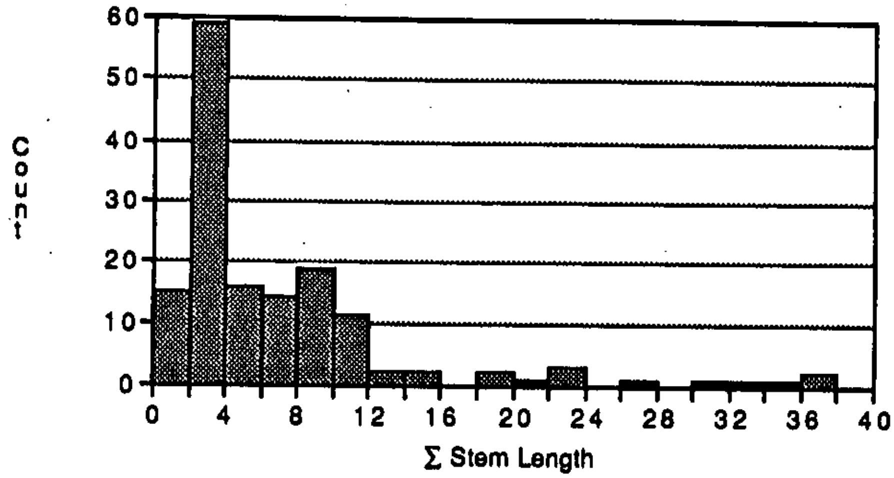


Figure 6. Nutlet output as a function of the number of glomerules of plants at Edgewood Park, 1990 and 1992. See Table 3 for line equations.



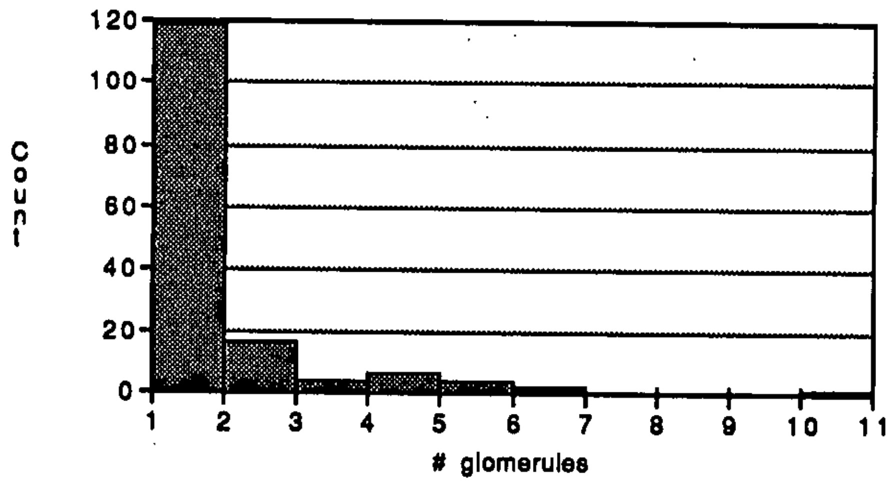
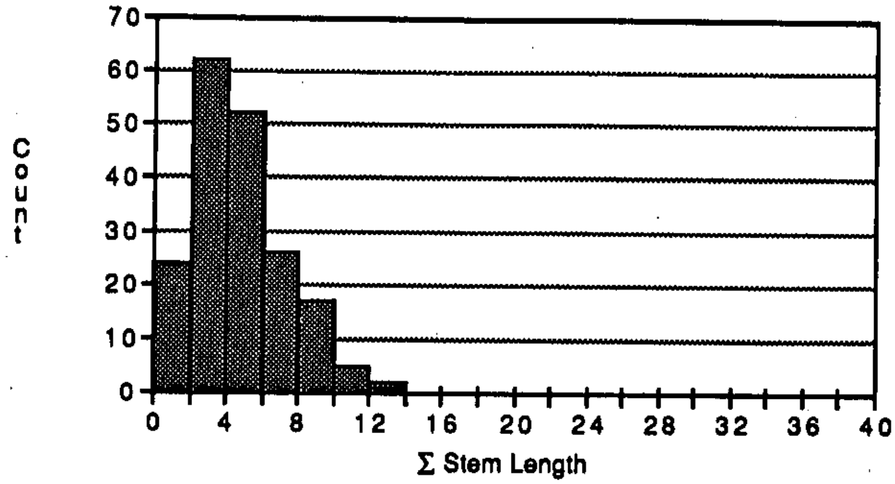


Figure 7. Plant size distributions (sum of stem length in cm and number of glomerules per plant) at Edgewood Park, 1992. n = 150.



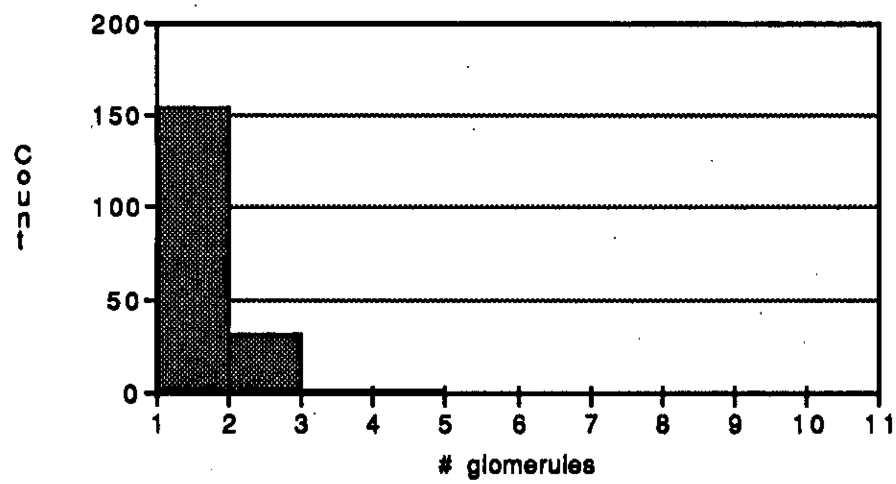


Figure 8. Plant size distributions (sum of stem length in cm and number of glomerules per plant) at Edgewood Park, 1990. n = 188.

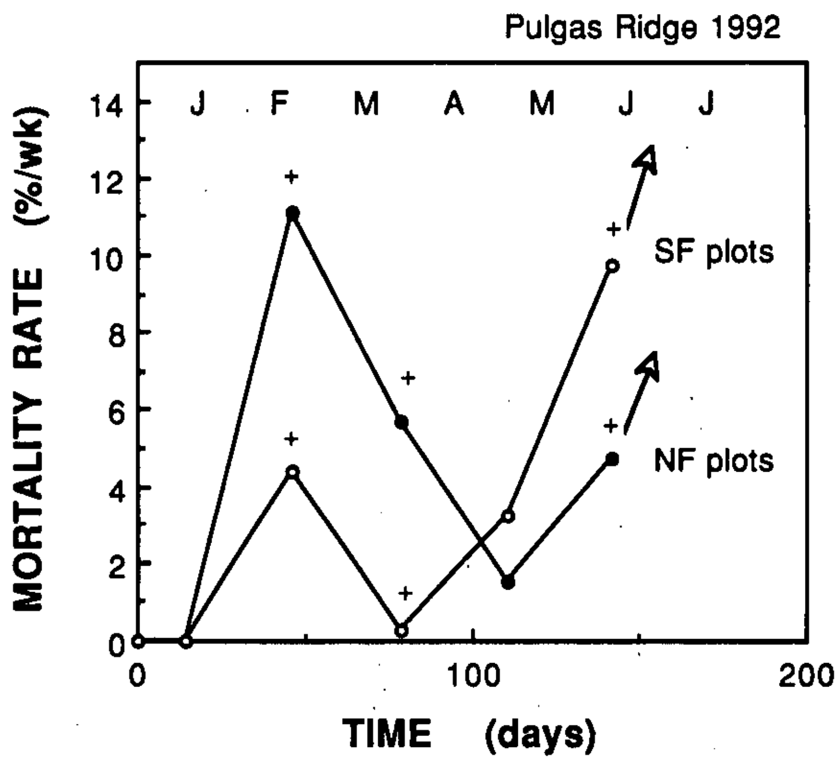


Figure 9. Mortality of A. duttonii in north-facing (NF) and south-facing (SF) plots at Pulgas Ridge, 1992. Day 0 = January 1, 1992. Significant differences between NF and SF mortality rates for the same time period are indicated with a "+".

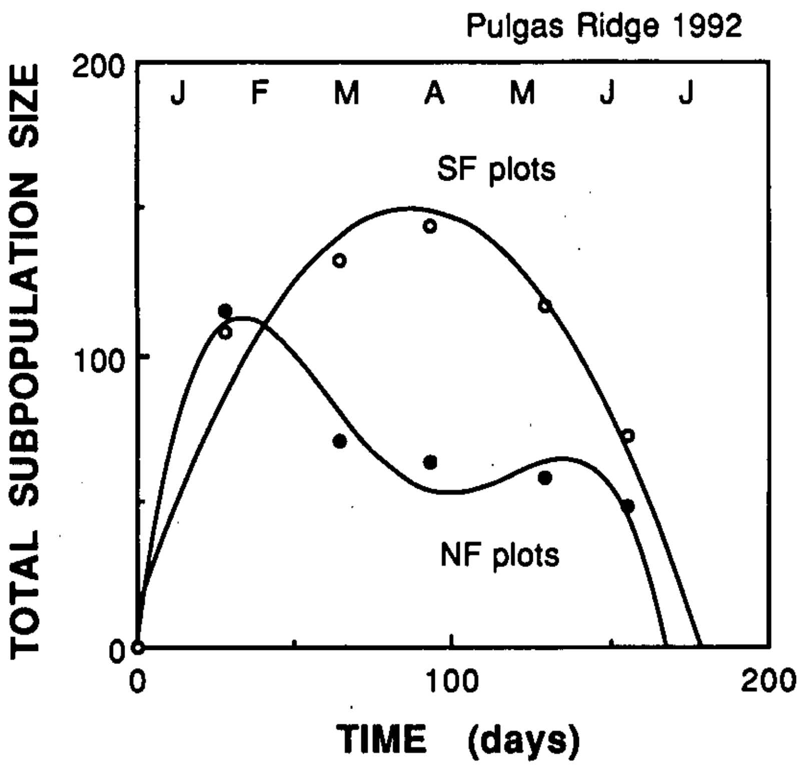


Figure 10. Growth of the north-facing (NF) and south-facing (SF) subpopulations of A. duttonii at Pulgas Ridge, 1992. Day 0 = January 1, 1992.

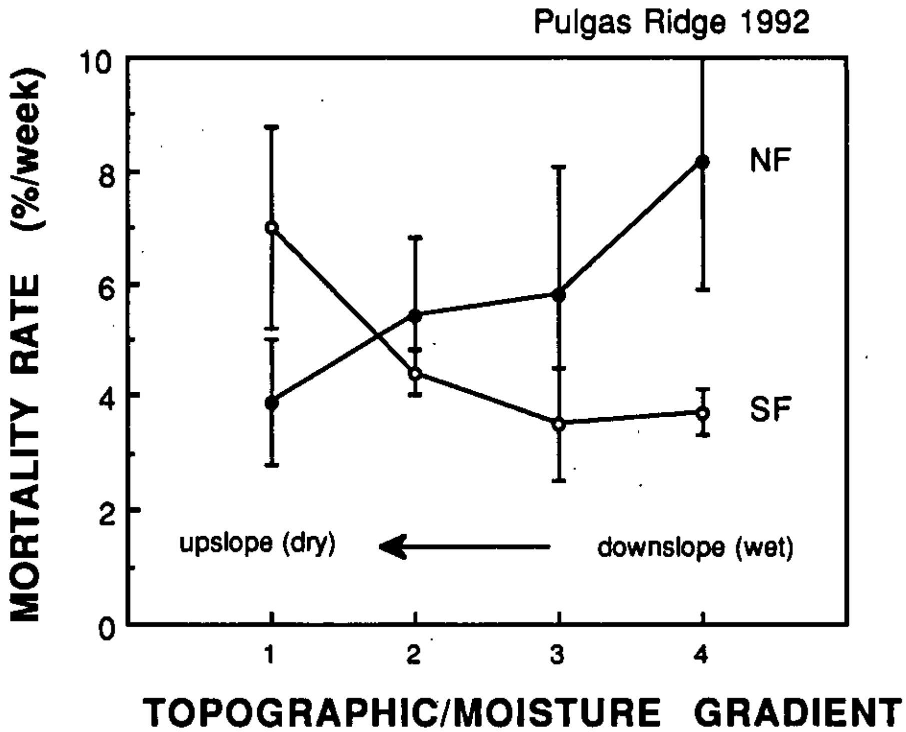
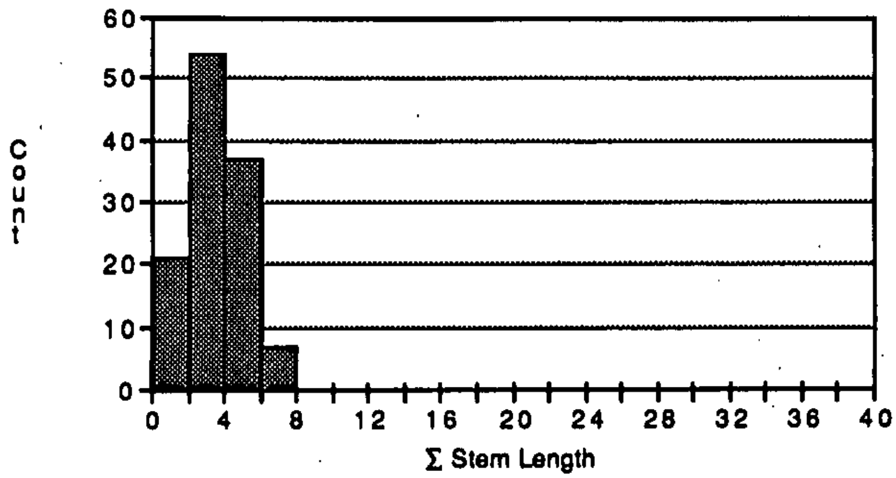


Figure 11. Mortality of A. duttonii in relation to aspect and position along a topographic-moisture gradient at Pulgas Ridge, 1992. Shown as means ± S.D.



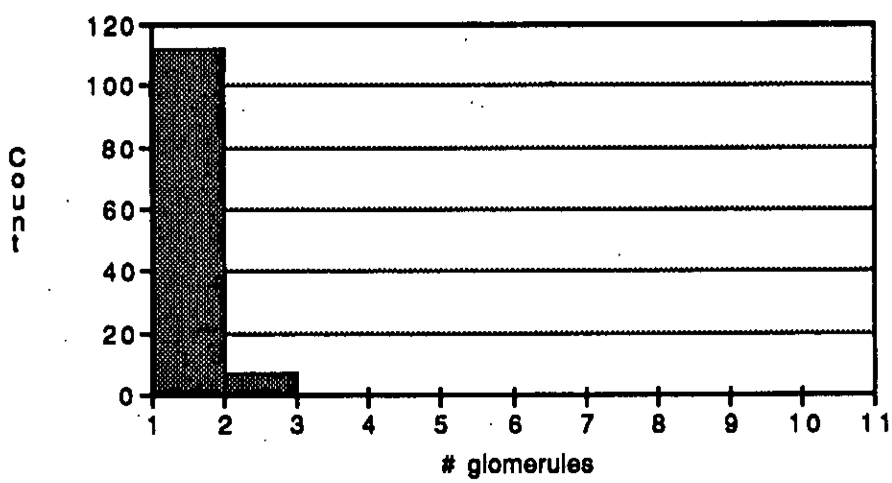


Figure 12. Plant size distributions (sum of stem length in cm and number of glomerules per plant) at Pulgas Ridge, 1992. n = 120.

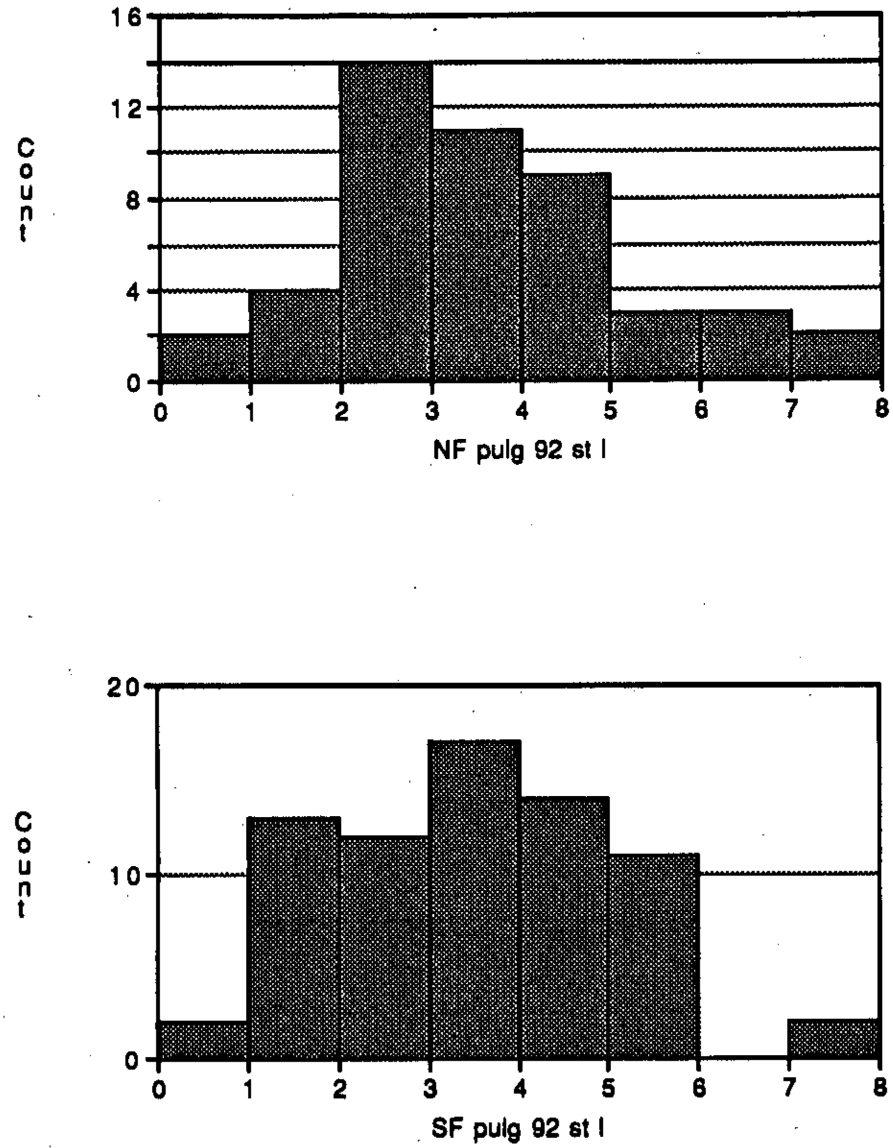


Figure 13. Plant size distributions (sum of stem length in cm) within north-facing (NF) and south-facing (SF) plots at Pulgas Ridge, 1992. n = 48 and 72, respectively.