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A model of ponderosa pine growth response to prescribed burning

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ABSTRACT

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Our objective was to model the radial growth response of individual ponderosa pines to prescribed burning in northern Arizona. We sampled 188 trees from two study areas, which were burned in 1976. Within each study area, control and burned trees were of similar age, vigor, height, and competition index. At Chimney Spring, trees were older, less vigorous, and taller and had a higher competition index than at Brannigan. For each tree, periodic basal area increment (PBAI) was calculated for the years 1974–1984. To determine which variable would best model growth, post-fire growth (1977–1984) was correlated with the 3 year average of previous growth, crown ratio, competition index, and diameter.

Post-fire growth response was modeled using stepwise multiple linear regression as a function of previous growth and indicator variables for treatment, treatment–site interaction, climatic variation, and treatment–year interaction. Independent variables of the final model included previous growth, climatic variation, and treatment–year interaction ($r^2=0.72$). Model coefficients indicated that fire affected growth significantly and negatively for 2 years, and then burned trees grew similarly to control trees. Differences in management history at the two sites did not affect growth after fire. We propose a linear aggregate model of variables controlling radial growth response of southwestern ponderosa pines to fire.

INTRODUCTION

Use of fire as a management tool is gaining increased importance in both wildland and managed forests. Fires are prescribed primarily to reduce fuel loading and hence the probability of uncontrolled, catastrophic fires, but they are also advocated to promote nutrient release and thinning. Determining the effect of prescribed fire on tree growth and productivity is important to managers and researchers alike.

Many environmental and treatment-related factors can affect growth re-

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sponse, and not surprisingly, studies of wild and prescribed fire effects on ponderosa pine growth have yielded contradictory results (Morris and Mowat, 1958; Lynch, 1959; Van Sickle and Hickmann, 1959; Wooldridge and Weaver, 1965; Pearson et al., 1972; Wyant et al., 1983; Landsberg et al., 1984); the response depended on how much damage the trees sustained or how their environment was affected.

The objective of this study was to delineate the factors that can affect growth response to prescribe fired, develop a mathematical model for predicting growth response to prescribed burning, and derive parameter estimates for southwestern ponderosa pine. (The resulting model is specific for ponderosa pine growing on basalt soil in the Flagstaff, Arizona, area.)

STUDY AREA HISTORIES AND CHARACTERISTICS

The two study areas, Chimney Spring and Brannigan Flat, are located 9 km apart, within the interior ponderosa pine type (Eyre, 1980) north of Flagstaff, Arizona. The stands are essentially monotypic. Both areas were prescribed burned in 1976 and have control plots within 500 m of burned areas. Soils are stony clay loams derived from volcanic cinders and basalt (Meurisse, 1971), and both areas are nearly flat (0–5% slope). The climate is cool and dry (Schubert, 1974).

Chimney Spring is a unit of the Forth Valley Experimental Forest, 10 km north of Flagstaff, at about 2270 m elevation. The overstory consists of uneven-aged ponderosa pine in groups (White, 1985). Dense thickets of young trees, less than or approximately equal to 70 years of age, occupy what were previously open areas between groups of mature trees. Chimney Spring has never been logged; however, it was grazed until 1926 (Pearson, 1933). Before Anglo-American settlement, Chimney Spring burned every 2–3 years, and the last fire occurred in 1876 (Dieterich, 1980). Chimney Spring has been the site of a prescribed fire research experiment since 1976; overall research design and objectives as well as fuel and burning conditions have been described by Sackett (1980) and Covington and Sackett (1986).

Brannigan Flat is more representative of managed ponderosa pine forests in northern Arizona. It lies within the Coconino National Forest, at about 2220 m elevation. Silvicultural records (Flagstaff District Ranger Office, Coconino National Forest, N. Highway 89, Flagstaff, AZ, 86004) indicate that Brannigan Flat was partially harvested in 1908, 1952, and 1971. The stand consists of pole-sized timber with an overstory of mature sawtimber growing in clumps. Brannigan Flat was precommercially thinned in 1974 (trees of less than 10 cm diameter at breast height (DBH) were cut), and the slash lopped and scattered. No records were available concerning the date of burning or burning conditions.

METHODS

Chimney Spring was sampled in autumn 1984 and 1985, and Brannigan Flat in autumn 1985. At both sites, subject trees were selected along a belt transect 20 m wide, but transect length varied. All transects ran southeast to northwest. At Chimney Spring, the study plots were 1 ha in size (100 m each side) and we sampled two control and two once-burned plots. No plot was more than 500 m distant from any other plot, and transects were 70 m long. An unsampled buffer zone 12 m wide was established inside plot perimeters to avoid effects from adjacent treatments. When there were insufficient trees to sample in the transect itself, subject trees were chosen near the transect, but not in the buffer zone (this occurred no more than five times per plot).

At Brannigan Flat, a control area (150 m×150 m) had been established before the fire. Both belt transects were 100 m long and had a 30 m buffer zone and the burned transect began 30 m north of the control area fireline.

Three diameter classes of trees were sampled: 20.3–30.5 cm DBH, more than 30.5–40.6 cm DBH and more than 40.6 cm DBH. On each transect, 50 trees in the size classes less than 40.6 cm DBH were numbered and chosen as a preliminary set. Only trees which met the following criteria were sampled: single bole (no forked trees), normal-appearing crown (no deformities indicative of disease or damage), no unusually heavy branching patterns, no visible insect or mistletoe infestation, and no apparent fire or lightning scars. From these 50 trees, 15 subject trees in the smaller size classes were selected randomly. Trees of more than 40.6 cm DBH were relatively rare, and virtually all trees on the plots that fit the criteria were selected (minimum 15). At each site, at least 45 trees were sampled in each treatment (188 for the entire study).

Data measured and recorded on each tree included DBH, total tree height to base of crown (crown base was defined as the height of the lowest green foliage), estimated competition from other ponderosa pines, and radial growth. Increment ones (two per tree) were taken at breast height 180° from each other if possible, and if not (e.g. a branch or branch scar was in the way), at least 90° from each other.

To estimate competition around subject trees, DBH of all trees that were sighted within a 2.3 m^2 ha^{-1} basal area factor wedge prism was measured with a diameter tape. Because fire-caused thinning occured, we also measured DBH of trees that died from the fire to estimate a thinning index as well as pre-burn competition.

Increment cores were prepared and crossdated using techniques described by Stokes and Smiley (1968). Growth rings were measured to 0.01 mm (Robinson and Evans, 1980).

The expression of growth used in this study is periodic basal area increment (PBAI (cm^2); Avery and Burkhart, 1983). Annual PBAI estimates were derived from the raw ring widths of a given year's growth using the average of two cores per tree, and the tree's diameter during any known year.

A dimensionless index of competition was calculated for each tree. Similarly, a thinning index was also calculated for the burned, dead trees around each subject tree, to quantify fire-related thinning. Competing trees were defined as those trees sighted in the prism within a distance of 40 times the subject tree diameter (Sutherland, 1989). Competition before the fire on the burned plots was estimated by adding to the data the diameters of trees that died from fire. The index used was

$$\left(\sum_{j=1}^{n} D_j\right)/D_i \tag{1}$$

where D_i is the diameter of subject tree for i trees, and D_j is the diameter of the jth competing tree.

Descriptive statistics (range, mean and standard deviation) were calculated for tree heights, crown ratios (crown length/tree height), tree ages (estimated to within 5 years), and competition indices. Distribution of these tree descriptors were compared using the Kolmogorov–Smirnov (K–S) two-sample test (Gibbons, 1976, p. 250).

In a series of simple linear regressions we correlated competition index, thinning index, crown ratio, diameter, previous growth, and growth since fire to determine which variable was most strongly correlated with growth since fire, to determine the relationships among variables, and to assess multicollinearity.

The data were tested for constancy of error variance over all observations and were natural logarithm-transformed where necessary (Neter et al., 1985, p. 615).

We used binary indicator variables to account for other potential sources of variation in post-fire growth. Climatic variation contributes significantly to growth variance in southwestern ponderosa pine (Fritts, 1976); we accounted for climatic variation effects with seven binary indicator variables (for each year since burning). We also used binary indicators for treatment effects, treatment–site interactions (treatment response caused by site differences), and treatment–year interactions (treatment response associated with time since burning).

We used one-half of the data set to develop models and reserved the other half to validate them, by assigning alternate trees to each set. The multiple linear regressions were performed with the development data set using a stepwise search procedure ($P<0.05$, F to include; Neter et al., 1985, pp. 430–431).

The regression coefficients were applied to the validation data set to predict growth each year after burning and the ratio of predicted residual mean square to observed residual mean square was assessed for difference from perfect agreement (a ratio of 1.0).

RESULTS

Statistics describing tree heights, crown ratios, estimated tree age, and diameters for both sizes are given in Table 1. Distributions of all descriptive variables (tree height, crown ratio, tree age, and competition index) are similar for burned and unburned plots, within sites ($D_{max} < D$, $P < 0.05$). However, in comparing the descriptors between sites, there are differences in all distributions ($D_{max} > D$, $P > 0.05$). The data indicate that compared with Chimney Spring, trees at Brannigan were shorter, had larger crown ratios, were younger, and had lower competition indices.

Correlations between the quantitative variables are given in Table 2. Previous growth was most strongly correlated with growth since fire, and was also significantly correlated with all other variables.

Not surprisingly, previous growth, competition index, crown ratio, and DBH were all significantly correlated with each other. All correlations were positive except for those related to competition indices. Crown ratio (vigor) and competition index were inversely and significantly related to each other; more vigorous trees grew in relatively less dense stands. Diameter was positively correlated with crown ratio and negatively with competition index; small trees with low crown ratios were in relatively dense stands, whereas large trees with high crown ratios had relatively less competition. Correlations between growth

TABLE 1

Descriptive statistics (range, mean, and standard deviation) of tree descriptor variables ($N = 45$–48); between study areas, all variables are distributed significantly differently (K–S test, $P < 0.05$), but there are no differences between treatments within study areas (K–S test, $P > 0.05$)

	Mean		Range	
	Control	Burned	Control	Burned
Height (m)				
Chimney Spring	18.8±3.76	20.2±6.25	12.2–27.4	11.4–34.4
Brannigan Flat	15.8±5.02	16.3±6.49	9.9–26.2	9.1–29.0
Crown ratio				
Chimney Spring	0.54±0.135	0.56±0.140	0.32–0.84	0.36–0.76
Brannigan Flat	0.63±0.129	0.67±0.119	0.40–0.92	0.45–0.89
Competition index				
Chimney Spring	15.1±6.73	15.3±5.09	4.9–29.2	5.3–26.0
Brannigan Flat	7.6±2.96	7.0±3.26	2.4–12.9	0.0–15.2
Age (5-year category)				
Chimney Spring	86±25	100±36	60–185	65–180
Brannigan Flat	95±55	85±43	50–190	50–170

TABLE 2

Simple correlation coefficients (r) between quantitative variables used in developing growth models

	Previous growth	Competition index	Crown ratio	Thinning index	DBH
Growth since fire	0.816[a]	−0.487[a]	0.549[a]	−0.089	0.562[a]
Previous growth	1.000	−0.584[a]	0.624[a]	−0.172	0.633[a]
Competition index		1.000	−0.568[a]	0.370[a]	−0.458[a]
Crown ratio			1.000	0.154	0.615[a]
Thinning index				1.000	−0.013
DBH					1.000

[a]Significant, $P<0.05$, $N=88$.

and diameter indicate that as tree size increased, growth before and after burning increased; large trees had relatively larger PBAI.

Thinning index was not significantly related to post-fire growth. Perhaps the fires did not cause enough thinning to affect post-fire growth, or the thinning offset damage from fire, resulting in no apparent overall effect. However, as there was no statistically significant relationship between fire-caused thinning and growth, thinning index was not included in any further analysis.

Of the other variables, previous growth, competition index, and crown ratio were significantly correlated with change in competition as a result of burning. The positive relationship between competition index and thinning index was reasonable; trees in dense stands are often suppressed and weak, and may be more susceptible to fatal damage from fire. Harrington (1987) found that smaller trees, the usual occupants of dense stands of southwestern ponderosa pine, were more susceptible to death from burning than larger, more open-grown trees. This may, in fact, partially explain why there was no relationship between thinning index and post-fire growth; the small trees that died were probably not effective competitors with the subject trees. Because there was no difference between lowest green foliage height distributions in control and burned trees at Chimney Spring or at Brannigan Flat ($D_{max}<D$, $P>0.05$), foliage loss was not considered as a potential variable. Similarly, thinning index was not included as an independent variable as there was not a significant relationship between this index and growth after burning. Crown ratio, competition index, and DBH were significantly correlated with previous growth, so, to avoid inferential problems associated with multicollinearity, we did not consider them in the model.

Using only the development data set, the dependent variable was individual tree ln(post-fire growth) of each year since burning, and the initial independent variable was previous growth. Stepwise addition of variables resulted in the following model (from the development data set only):

$$\ln(\mathrm{PFG}) = -0.014 + 0.907\ln(\mathrm{PRG})^* - 0.376\mathrm{Y1} + 0.020\mathrm{Y2} + 0.203\mathrm{Y3}^* + 0.203\mathrm{Y4}^* - 0.204\mathrm{Y5} + 0.099\mathrm{Y6} + 0.048\mathrm{Y7} - 0.254\mathrm{TY1}^* - 0.197\mathrm{TY2}^* - 0.108\mathrm{TY3} + 0.025\mathrm{TY4} + 0.025\mathrm{TY5} - 0.010\mathrm{TY6} + 0.045\mathrm{TY7}$$

where PFG is post-fire growth, PRG is previous growth, Y1 is year 1 after fire (1977)...Y7 is year 7 after fire (1983), TY is treatment–year interaction, and the intercept, β_0, took into account year 8 (1984); variables with an asterisk indicate significant t-values for the coefficients ($P<0.05$). Inclusion of treatment and treatment–site interactions did not add to explicable variance.

Significant autocorrelation ($r_1=0.567$, Durbin–Watson statistic 0.865, $P<0.05$) implied an important relationship between growth of one year and the following year, effectively reducing the model degrees of freedom. We estimated the effective degrees of freedom (N') as

$$N' = N(1-r_1)/(1+r_1)$$

(Mitchell et al., 1966) where $N=88$ trees$\times$8 years$=704$ and $N'=194$. The F-value of the final model was 118.952 ($P<0.001$). Overall, the model explained 72% of total growth variance since burning (adjusted multiple $r^2=0.722$).

Some of the coefficients associated with sets of variables (years and treatment–year interactions) did not have significant t-values, but were not dropped from the equation. These coefficients represented categories which were being compared with each other to assess for differential effects (Nie et al., 1975), and because significant autocorrelation existed, and the years themselves could not be considered separately (Neter et al., 1985, pp. 444–448).

Signs of the estimated coefficients were as expected; the relationship between ln(PRG) and ln(PFG) was positive. Signs of the years-since-burning coefficients fluctuated, as might be expected, with climatic variation. Annual precipitation and temperature for Flagstaff for the hydrologic years (1 October–30 September) 1977–1984 (National Oceanographic and Atmospheric Administration, 1984) are plotted in Fig. 1. Water availability limits ponderosa pine growth (Fritts, 1976, pp. 240–241), and we would expect low growth during drought years (low precipitation, often with high temperatures). The coefficient for year 1 after burning (1977) was relatively large and negative; although temperature was below average, precipitation was far below average. Years 3 and 4 (1979 and 1980) had significant, positive coefficients, when years were cool and wet.

Over the entire time period, there was no significant treatment effect, but treatment–year interactions indicated that growth responded to treatment with time. The treatment–year interaction was significant and negative for 2 years

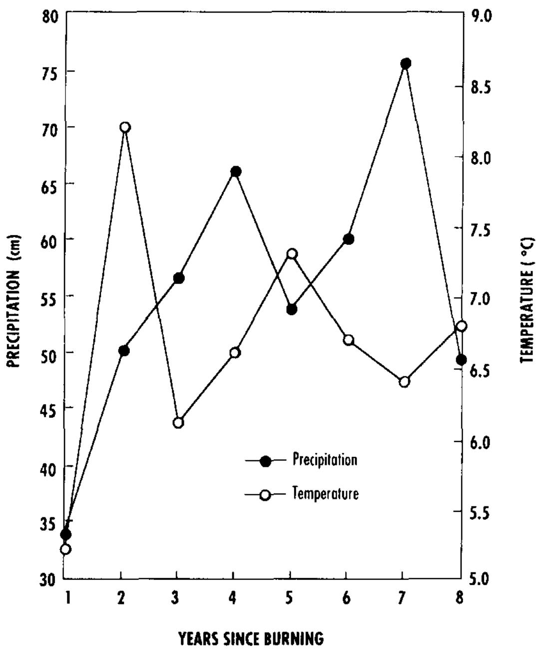

Fig. 1. Annual precipitation and temperature at Flagstaff, AZ, during the years after burning (hydrologic years 1977–1984).

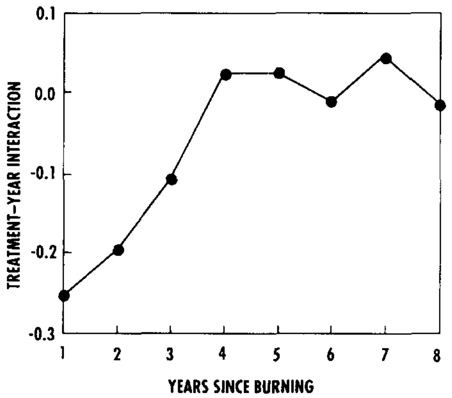

Fig. 2. Coefficients of the treatment–year interaction in the multiple regression model, vs. years after burning (1977–1984). Only coefficients for the first 2 years after fire had t-values significantly different from zero.

immediately after fire. No other treatment–year interaction coefficients were significant, but they gradually became less negative and varied around zero. This growth response to burning is illustrated in Fig. 2. For the first three years after the fires (1977–1979), coefficients were negative, but less negative with each succeeding year. By year 4 (1980), the values had apparently stabilized, and varied around zero. Autocorrelation in the series effectively smoothed this curve; without it, the year 1 (1977) value would probably be more negative, and one or more values after year 4 (1980) might be positive. However, the curve as it is and the t-values of the coefficients show that there were early, negative effects of burning on ponderosa pine growth, but these effects were short lived (only 3 years). Reinhardt and Ryan (1988) found a similar response in prescribed-burned *Larix occidentalis*, where negative effects lasted only 1 year and growth significantly increased for 4 years.

This model validated well. The residual mean square of the equation was 0.1243. The mean square of values of the validation data set minus values predicted from the model was 0.1290. These mean squares have a ratio very close to one (1.04), which means that the model adequately predicted the validation data set (Snee, 1977).

DISCUSSION AND CONCLUSIONS

The strong and positive relationship between previous growth and post-fire growth suggests that factors affecting tree growth rate before the fire continued to affect post-fire growth; trees that grew well before the fire grew well after the fire. Trees that grew well had fewer competitors, were large, and had high crown ratios.

Management history did not affect growth response to burning (indicated by non-significant contribution of site–treatment interaction to explained variance). The two study areas had different management histories: Chimney Spring was protected from logging and grazing, whereas Brannigan Flat was grazed continually since settlement, logged several times, and thinned before burning. In this case, differences in management history resulted in different competition levels, and the correlation analysis indicated an inverse relationship between post-fire growth and competition. Chimney Spring had significantly higher competition levels than Brannigan Flat. The fact that site–treatment interaction is not an important contributor to growth variance implied that, in this case, management history itself is not an important factor in determining growth response to burning. Thus, the important difference between the study areas was stand density, and not thinning history.

The results from the model suggest that there was a significant decrease in growth of burned trees for 2 years at both study areas (Fig. 2). After that, burned-tree growth stabilized and was similar to that of control trees. There were no significant positive growth effects on burned trees in the 8 years after fire. Similarly, Chambers et al. (1986) noted that, in general, conifer growth recovery after burning occurred within 2–3 years.

What fire-related factor(s) were responsible for the observed growth response? Increased stem growth proportional to fire-related thinning in ponderosa pine has been noted by Morris and Mowat (1958), Lynch (1959), Van Sickle and Hickman (1959), and Pearson et al. (1972). In our study, however, stand density was high, and little thinning occurred; Schubert (1971) noted that under high stand density conditions, southwestern ponderosa pine responds slowly to thinning.

Other studies have found foliage loss to be an important determinant of growth response to burning. Pearson et al. (1972) found that, after an Arizona wildfire, trees with less than 60% foliage exhibited increased growth. Alternatively, Wyant et al. (1983) attributed an increase in shoot growth to removal of lower, less efficient foliage, and improved photosynthetic efficiency. We inferred from lowest green foliage height comparison that there was probably no significant foliage loss after the fire at our sites, so foliage loss was not a likely contributing factor to decreased growth.

The effect of cambial damage on growth of burned ponderosa pine trees has not been studied, but could reasonably contribute to decreased growth after burning. Mortality has been related to severe bole burning in ponderosa pine (Lynch, 1959; Wyant et al., 1986). Ryan et al. (1988) found that the number of dead cambium samples in *Pseudotsuga menziesii* trees was the most important predictor of mortality after prescribed burning. In our initial sampling, trees with fire scars or bark sloughing were excluded from the sample, which eliminated the most severely damaged trees. The correlation analysis showed a positive relationship between post-fire annual growth and diameter. This result could have occurred because larger trees generally have thicker bark, and bark insulates cambium from heat. Cambial damage probably occurred to smaller trees.

Trees may have experienced root damage from the fires. The fire at Chimney Spring was observed to be of low intensity but of localized long duration; some deep organic debris smoldered for 2–3 days (Sackett, 1980). Low heating over a long period of time could kill shallow roots (Hare, 1961). Chambers et al. (1986) noted that these roots, usually fine feeder roots, should quickly regenerate in a healthy tree, during favorable environmental conditions. Notably, the year after the fire in this study (1977) was an extreme drought year. These conditions would not have favored quick root recovery.

No factor that we could measure appeared to be responsible for the observed lower basal area growth for the first few years after burning. In fact, improved nutrient relations (Harris and Covington, 1983; Covington and Sackett, 1986; Ryan and Covington, 1986) and water availability (Haase, 1986) should have contributed positively to growth. However, where fire did cause cambial and root damage, nutrient and water uptake could have been inhibited (especially under drought conditions), and trees may have directed available photosynthates to repair, not new cambial growth. Of all woody tissue, cambium has the lowest priority for photosynthate allocation (Waring, 1983). Four years after the fire, nutrient levels were similar to those before the fire, so perhaps when damage was repaired, the cambium could not benefit from the nutrient pulse. In any case, growth was more limited by negative factors than promoting factors for the first years after the fire.

Our study areas were burned with a single prescribed fire after a century of fire exclusion; response to burning may be different following repeated fires. There should be less fuel, particularly by the third fire, as the first fire may produce even more fuel than existed before the initial fire (Sackett, 1980). Thinning from fire should decrease with each successive fire, as weak individuals die. If nutrient release continues to occur with repeated burns, as indicated by Covington and Sackett (1986), then stem growth may increase. A study of growth in areas repeatedly burned should clarify these questions.

The results of this study are clear, although the mechanisms causing them are not yet conclusively resolved. Although we attempted to eliminate and account for factors related and unrelated to fire that affect growth, we found that there were important potential fire-related factors, that, 8 years after the fire, we could not directly measure or relate to growth (for example, foliage loss, change nutrient relations, and root damage). From literature cited earlier in this paper, and our results, we propose the following linear aggregate model for southwestern ponderosa pine growth response to fire in the *i*th year of *n* years since burning:

$$PFG_i = PC + CD + RD + FL + TI + \delta N + \delta W + Y_i + TY_i$$

where PFG is post-fire growth, PC is the previous condition, CD is cambial damage, RD is root damage, FL is foliage loss, TI is thinning, δN is change in nutrient availability, δW is change in water availability, Y is an indicator for year since burning, to account for climatic variability, and TY is an indicator for treatment–year interaction, to account for response and recovery. Coefficients would indicate the proportional post-fire growth limitation of given variables. The signs of the coefficients are predictable. Sign of the previous condition coefficient could be positive or negative, root and cambial damage would always be negative, foliage loss could be negative or positive, nutrient and water availability losses would probably be positive, and sign of the year coefficient would depend on climate for that year.

Studies of growth response to fire (or indeed, any environmental disturbance) must delineate and factor out the general and site-specific variables related and unrelated to treatment than can affect tree growth. Only then can fire effects be quantified, and appropriate fire management programs implemented.

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