Effect of Periodic Burning on Soil Nitrogen Concentrations in Ponderosa Pine[1]

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ABSTRACT

To determine the effects of different burning intervals on soil N status in substands of sapling-, pole-, and sawtimber-sized ponderosa pine (*Pinus ponderosa* Laws.) we sampled plots burned at 1-, 2-, and 4-yr intervals by three strata at two depths (0-5 and 5-15 cm). Generally, NH_4^+; and NO_3^- concentrations were higher on plots repeatedly burned than on unburned controls. However, plots not reburned for 4 to 5 yr had concentrations similar to controls. No significant difference in total (organically bound) N was found among treatments. We conclude that frequent periodic burning can be used to enhance N availability in southwestern ponderosa pine sites.

Additional Index Words: **fire effects, NH_4^+, NO_3^- , *Pinus ponderosa* Laws., Arizona, fuel management.**

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EFORE EUROPEAN SETTLEMENT Of northern Arizona in the 1860s, natural fires were frequent in ponderosa pine *(Pinus ponderosa* Laws.) forests, perhaps occurring every 2 to 3 yr (Dieterich, 1980). For the past 60 to 100 yr fires have been excluded throughout much of this forest due both to active fire suppression and to grazing (which reduced herbaceous fuels and broke the continuity of the forest floor). Decades of fire exclusion in ponderosa pine have been blamed for everything from increased fuel loads, with associated increases in fire severity, to reduced growth and stagnated nutrient cycles (Cooper, 1960; Biswell, 1972; Weaver, 1974). Recently, forest managers have been using prescribed (controlled) burning in the ponderosa pine type, primarily to reduce fuel loads.

Since ponderosa pine growth often is severely limited by low nitrogen (N) availability (e.g., Powers, 1980; Heidmann et al., 1979; Cochran 1979), a major concern has been fire impacts on soil N pools. One concern is the possible decrease in the total N capital of the site because substantial amounts- of N may be volatilized during burning (Wright and Heinselman, 1973; Klemmedson, 1976). However, fire exclusion has also been blamed for degrading the N economy (Biswell, 1972; Wright and Heinselman, 1973; Bennett, 1974), by allowing forest litter to steadily accumulate, hence retarding organic N mineralization into NH_4^+ and NO_3^-.

Although some data exist for the effects of initial burning on soil N pools in ponderosa pine (Ryan and Covington, 1986), no data have been published concerning the effects of repeated burning. Since current land management plans for southwestern ponderosa pine include frequent burning for fire hazard control, assessment of the effects of repeated burning on soil N is needed. This paper presents the results of a study of the effects of periodic burning, at 1-, 2- and 4-yr intervals, on total N, ammonium-nitrogen (NH_4^+-N), and nitrate-nitrogen (NO_3 -N) in the mineral soil of a ponderosa pine ecosystem near Flagstaff, AZ. Previous studies at the site had found that fire behavior and ecosystem responses (e.g., changes in moisture, nutrients, and production) varied greatly among patches dominated by saplings, poles, and sawtimber (Harris and Covington, 1983; Covington and Sackett, 1984; Ryan and Covington, 1986). Therefore, the soil sampling scheme and data analysis were designed to compare treatments within the three tree size strata (sapling, pole, and sawtimber).

METHODS

Study Area

The study area is part of the Fort Valley Experimental Forest, approximately 10-km northwest of Flagstaff, AZ, at an elevation of 2195 to 2255 m (11°45' W, 35°16' N). The climate is described by Schubert (1974) as subhumid to humid with cool temperatures and early summer drought. Mean annual temperature at the Fort Valley weather station between 1909 and 1968 is 7°C; mean annual precipitation is 57.4 cm, with about half falling as snow. The average frost-free growing season is 94 d.

Soils are derived from basalt and cinders and are tentatively classified' as Brolliar stony clay loam (fine montmorillonitic, frigid Typic Argiborolls) by an adjacent soil survey (unpublished sails report by R. T. Meurisse, Coconino National Forest, USDA Forest Service).

The study area, typical of virgin ponderosa pine, is dominated by an uneven-aged forest in small, more or less evenaged groups. Pole=sized trees, 10- to 28-cm diameter at breast height (dbh) and 60- to 100-yr-old, are the predominant size class, with scattered groups of older trees, 28- to 120-cm dbh and 200- to 500-yr-old, and dense thickets of sapling-sized trees ranging from 1.5- to 10-cm dbh and 60- to 70-yr-old. The distribution by size class on the study area was: saplings, 2750/ha; poles; 770/ha; and sawtimber, 130/ha (Sackett, 1980). Trees < 1.4-m tall (breast height) were 975/ka. Basal area averaged 33. ml/ha. The relative canopy area of each overstory stratum on the experimental plots was: sawtimber, 17.3%; pole, 62%; sapling, 17.0%; with 3.7% remaining as small openings, (Sackett, 1984).

The site is unharvested except for localized fuelwood cutting of dead trees near roads. Based on fire scar analysis, Dieterich (1980) determined that the last wildfire on the study area occurred in 1876. Before that, fires occurred at an average interval of about 2 yr. Initially, fire exclusion was probably caused by heavy grazing, which began in the 1870s, with active fire suppression beginning just after the turn of the century.

Experimental Design and Treatments

Twenty-seven contiguous 1-ha plots were established in the study area in 1976. Six treatments (periodic burning every 1, 2, 4, 6, 8, and 10 yr) with three replicates each plus controls (and extra unburned plots) were assigned at random to each. Each plot had a 1.5-m wide fireline plowed around its perimeter.

Three separate comparisons of fire effects on soil N were made. First, soils were sampled in the 1-, 2-, and 4-yr interval plots before

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the fourth reburning period in the fall of 1980. In 1980 the 1-yr plots had one initial burn and three repeat burns; the 2-yr plots had one initial burn and one repeat burn; and the 4-yr plots had only an initial burn.

Time constraints and an early snowfall precluded our sampling the controls in 1980. Second, to determine the effects of reburning the 4-yr plots, we sampled them and the controls in the spring of 1981. Finally, in the fall of 1981, we sampled the reburned 4-yr plots and the once-burned 10-yr plots, as well as the controls to determine the duration of the reburning effects.

Initial burning treatments were applied at night on 5 Nov. 1976, mostly using strip headfires, with 9 to 12 m between strips, and some backing fires early in the evening (Sackett, 1980). See Brown and Davis (1973) for fire management terminology. Air temperatures dropped from 15°C at 1730 h to 3°C at 2400 h when most of the flaming combustion was complete. Relative humidity increased from 21 to 48% during the same period.

Fuel moisture content was estimated for three layers of the forest floor in accordance with standard fire behavior fuel designations (Brown and Davis, 1973; Sackett, 1979). These layers coincide with earlier forest soils terminology (Lutz and Chandler, 1946) as well. The O1 horizon is separated into the highly flammable L-layer, composed of recently cast litter (mostly pine needles in our case), and the F-layer, litter that is starting to discolor and break down. The O2 horizon is designated as the H-layer in fire behavior considerations. Burning forest floor material had moisture contents of 80 to 120 g/kg in the L-layer, and 100 to 190 g/kg in the F- and H-layers.

Sample Collection

Fuel sampling procedures are described in Sackett (1980). Forest floor weights were determined by collection 64 0.093-m^2 samples per plot, while larger fuels were inventoried by the planar intersect technique of Brown (1974). Forest floor weights are reported as ash-free dry weight (determined by loss on ignition).

Mineral soil samples, composited from 10 to 15 randomly located samples each, were collected from 0- to 5 and 5- to 15-cm depths using a 2.5-cm diam soil sampling tube. For each burning treatment, a total of nine-composite samples (three from each replicated 1-ha plot), was taken for each overstory stratum, representing a total of 90 to 135 individual tube samples.

Soils were sieved (2 mm) immediately in the field and a 10- to 20-g subsample for NH_4^--N and NO_3-N analysis was added to a 125-mL bottle containing 100 mL of 2 *M* KCL (acidified with HCl to pH = 2.5); the bottle and extractant had been preweighed. The extractant contained I mg/kg phenyl mercuric acetate as a preservative. .The soil's field weight was determined by a second weighing of the tared bottle and extractant, and its dry weight determined from a second sample dried in a forced air oven at 105°C until weight loss ceased. The remainder of the composite soil sample was placed in a paper bag and returned to the lab where it was air dried for total N analysis.

Chemical Analysis

All N data are reported as elemental N, whether in the organic, NH_4^+, or NO_3^- form, i.e., as either total N, NH_4^+-N, or NO_3^--N. Mineral N was determined colorimetrically on the KCI extract using the Technicon AutoAnalyzer, within 2 d of sampling. An aliquot of the extractant was pipetted into a clean bottle after 24 h of extraction time to prevent contamination from organic matter breakdown. Samples were stored at 1°C before analysis. Auto-Analyzer methods (Anonymous, 1974) were: NO_3^--N, Technicon Industrial Method no. 100-70W; NH_4^+-N, Technicon Industrial Method no. 98-70 W/A; total N, the Berthelot reaction as described by Schuman et al. (1973). For total N, 1 to 2 g of air-dried soil was digested using the selenium-catalyzed, sulfuric acid, hydrogen peroxide, lithium sulfate technique of Parkinson and Allen (1975). The digest was then analyzed on the AutoAnalyzer.

Statistical Analysis

Since factorial analysis of variance (AOV) showed highly significant interactions between treatment, stratum, and depth, one-way AOV's were run for each depth-treatment-stratum-date combination. Statistical comparisons (p = 0.05) for a particular sampling date were by Scheffe's test for three means.

RESULTS

Burn Description

The initial fires spread at rates of 1.2 to 1.8 m/min, sometimes increasing to as much as 3.7 m/min. Flame lengths in surface needles seldom exceeded 40 cm. Flaming combustion was evident mostly in surface needles and the upper portion of the F-layer. Glowing combustion was effective in consuming the more decomposed portions of the F- and H-layer, where deep forest floor accumulations were present. On 93% of the area, L-layer material was consumed. F-layer material was consumed on about 61% of the area and H-layer material was consumed on 18% of the area.

Forest floor material <2.5 cm in diameter was reduced from 33.9 to 12.7 Mg/ha by the initial burn. Larger material was reduced from 16.0 to 4.9 Mg/ha by the initial burn. Consumption of forest floor materials was greatest where deep accumulations were burned to mineral soil in groups of old, large trees. Sapling, pole, and sawtimber strata have quite different microclimates and forest floor characteristics, hence they exhibited different fire behavior and consumption rates. The predominant pole-sized stratum had about 52 Mg/ha of material on the ground, whereas open, sawtimber-sized groups had as much as 90 Mg/ ha. Dense stands of Sapling-sized trees had about 30 Mg/ha. Generally, fire behavior and forest floor consumption were directly related to forest floor loadings. Combustion was greatest in open sawtimber stands, less in closed-canopy pole stands, and least in sapling thickets. The impact of this initial burn on nutrient and organic matter storage in woody litter and forest floor are reported in Covington and Sackett (1984).

Table 1 illustrates the ambient conditions, fire characteristics, and results on fuel loads of repeat burns. Fire behavior during repeat interval burns was different from initial burns due to drastically changed fine fuel conditions. Needle cast after initial burns did not become incorporated with residual forest floor material, in contrast to unburned sites. Instead, 1-, 2-, or 4-yr of needles remained unincorporated on the surface providing more available fuel for flaming combustion and more dramatic fire behavior. However, under marginal burning conditions (damp, cold weather), these unincorporated needles were still difficult to burn. Thus, burning late in the fall, when burning conditions are poorer, drastically reduces the chances for successful prescribed burning

Table 1. Burning conditions, fire behavior, and forest floor consumption for rotational prescribed burns after initial burns.

	Year of reburn						
	1977	1978		1979	1980		
Interval (yr)	1	1	2	1	1	2	4
Date of burn	3 Nov.	9 Nov.	9 Nov.	6 Nov.	31 Oct.	24 Oct.	2, 3 Oct.
Litter accumulation since last burn (Mg/ha)	1.23	1.95	2.22	2.45	1.86	2.02	7.48
Litter consumed (Mg/ha)	0.71	†	†	2.57	‡	3.61	6.54
Litter moisture content (g/kg)	70-80	80-140	80-140	100-130	80-100	50-110	30-80
Air temperature (°C)	18-20	13	13	12	15	12-15	23-29
Relative humidity (%)	22-28	41-45	41-45	45	30	22-28	13-22
Rate of fire spread (m/h)	21	†	†	†	‡	53	227
Area burned (%)	47	†	†	†	‡	90+	100

†Burning conditions too marginal to take measurements.
‡Time constraints precluded fire behavior and post-burn measurements.

Table 2. Mean concentrations of NH_4^+-N for southwestern ponderosa pine surface soils burned at different intervals. Data are means (standard errors), n = 9 composite samples.

Stratum and depth	Burning interval (no. of burns)		
	1 yr (4)	2 yr (2)	4 yr (1)
	mg/kg		
Sawtimber			
0- 5 cm	13.78 (1.655)a†	10.64 (1.055)a	2.83 (0.383)b
5-15 cm	10.51 (0.718)a	7.95 (0.548)b	2.01 (0.105)c
Pole			
0- 5 cm	11.85 (1.307)a	11.37 (1.129)a	2.03 (0.093)b
5-15 cm	8.91 (0.600)a	8.88 (0.5961a	2.01 (0.058)b
Sapling			
0- 5 cm	14.33 (1.315)a	10.90 (1.185)a	2.03 (0.147)b
5-15 cm	10.01 (0.853)a	8.61 (0.482)a	2.08 (0.102)b

† Means within stratum and depth classes followed by different letters differ at $p = 0.05$.

Table 3. Mean concentrations of NH_4^+-N of the 0- to 5-cm depth for different burning intervals.

Stratum and sampling date	Burning interval		
	Control	4 yr	10 yr
	mg/kg		
Sawtimber			
Fall 1980		2.83 (0.383)	
Spring 1981	4.68 (0.451)a‡	17.75 (5.580)a	
Fall 1981	1.51(0.373)a	1.95 (0.360)	1.21 (0.116)a
Pole			
Fall 1980		2.03 (0.093)	
Spring 1981	3.22 (0.359)a	6.97 (1.808)a	
Fall 1981	0.96 (0.165)a	1.06 (0.117)a	0.93 (0.132)a
Sapling			
Fall 1980		2.03 (0.147)	
Spring 1981	2.62 (0.184)a	6.40 (1.882)a	
Fall 1981	0.64 (0.081)a	1.06 (0.117)b	0.76 (0.072)a

† Similar patterns were found for the 5- to 15-cm depth. Data are means (standard errors) $n = 9$ composite samples.
‡ Means for the 0-5 cm depth within stratum and sampling date classes followed by different letters differ at $p = 0.05$.

Soil Nitrogen

The general pattern for soil N (Tables 2-5) was one of greater concentrations in the sawtimber stratum than in the pole and sapling strata, although there are some exceptions. This pattern agrees with previous work at the study area the 1st yr after the burns (Ryan and Covington, 1986). Also, as would be expected, the 0- to 5-cm depth had greater N concentrations than the 5- to 15-cm depth.

Fall 1980 Before Burning

Because we did not sample the controls in 1980, direct comparisons are possible only among 1-, 2-, and 4-yr interval plots (Table 2). However, since the 10-yr plots (not reburned for 5 yr) were almost identical to controls for all forms of N measured in the fall of 1981 (Tables 3-5), we suspect that the control data for the fall of 1980 would have been very similar to that of the 4-yr plots (not reburned for 4 yr).

The only significant differences among 1-, 2-, and 4-yr plots in the fall 1980 were for NH_4^+-N. Generally, NH_4^+-N concentrations were significantly greater, by factors of 3 to 5, in the 1- and 2-yr interval plots than in the 4-yr interval plots (Table 2) and presumably, the controls. This was true for all three strata, and at both depths. Generally the response was greater for the 0- to 5-cm depth than the 5- to 15-cm depth. That the NH_4^+-N and NO_3^--N concentrations of the burned sapling stratum were approximately equivalent to those of the burned pole and sawtimber strata was surprising. Ryan and Covington's (1986) results following the initial burning of our study site showed no detectable change in mineral N in the sapling stratum.

Spring 1981 After Reburning

Although the 4-yr plots were quite low in NH_4^+-N in the fall of 1980, reburning appeared to cause substantial increases (Table 3). However, due to high NH_4^+-N variability, particularly in the reburned plots, these differences were not significant.

Nitrate-N concentrations were increased even more dramatically by the returning (Table 4). The highest concentrations were in the burned sawtimber stratum at the 0- to 5-icm depth where .they averaged 6 mg/kg, the highest to date at our study area. Nitrate-N was significantly higher, by factors of 20 to 125, on the reburned 4-yr plots than the controls for all strata and at both depths. Reburning did not significantly alter total N content for any stratum at either depth (Table 5).

Fall 1981 After Reburning

In the fall of 1981 we sampled both reburned 4- and 10-yr plots, which.had an initial burn in 1976, at the same time the 1-, 2-, and 4-yr interval plots were first burned.

Table 4. Mean concentrations of NO_3^--N of the 0- to 5-cm depth for different burning intervals. †

Stratum sampling date	Burning interval Control	4 yr	10 yr
	mg/kg		
Sawtimber			
Fall 1980		0.40 (0.069)	
Spring 1981	0.23 (0.156)a‡	6.18 (1.704)b	
Fall 1981	0.18 (0.162)a	0.58 (0.361)a	0.13 (0.076)a
Pole			
Fall 1980		0.03 (0.006)	
Spring 1981	0.02 (0.009)a	0.63 (0.2091b	
Fall 1981	0.01 (0.007)a	0.04 (0.004)b	0.01 (0.002)a
Sapling			
Fall 1980		0.02 (0.002)	
Spring 1981	0.01 (0.004)a	0.79 (0.248)b	
Fall 1981	0.01 (0.004)a	0.04 (0.010)b	0.01 (0.001)a

† Similar patterns were found for the 5- to 15-cm depth. Data are means (standard errors), n = 9 composite samples.
† Means within stratum and sampling date classes followed by different letters differ at p = 0.05.

Table 5. Mean concentrations of N of the 0- to 5-cm depth for different burning intervals. †

Stratum and sampling date	Burning interval Control	4 yr	10 yr
	mg/kg		
Sawtimber			
Fall 1980		1570 (113)	
Spring 1981	1650 (90)	1670 (95)	
Fall 1981	1590 (115)	1190 (107)	1540 (128)
Pole			
Fall 1980		1140 (33)	
Spring 1981	1220 (100)	1120 (34)	
Fall 1981	1170 (104)	1050 (38)	1140 (80)
Sapling			
Fall 1980		1160 (62)	
Spring 1981	1180 (85)	1150 (74)	
Fall 1981	1100 (70)	1060 (60)	1220 (90)

† Similar patterns were found for the 5- to 15-cm depth. Data are means (standard errors), n = 9 composite samples. There were no significant differences (p = 0.05); standard errors were 4 to 8% of the mean.

Although NH_4^+-N seemed slightly higher on the reburned 4-yr plots than the controls (Table 3), only the differences for the sampling plots were statistically significant. The once burned, 10-yr plots were almost identical to the controls in NH_4^+-N concentrations.

As was the case for NH_4^+-N, differences in NO_3^--N between reburned and control plots were not so striking in the fall as they had been in the spring of 1981 (Table 4). Nitrate-N appeared to be higher on reburned than control plots for all strata and both depths; however, significant differences were restricted to the 0- to 5-cm depth for pole and sapling strata only. The highest NO_3^--N concentrations were in the reburned 4-yr plots' sawtimber stratum, but high variance in the burned plots caused these differences not to be significant. Again, the once burned 10-yr plots were very similar to the controls in NO_3^--N. There were no apparent differences among treatments in total N.

In summary, burning at I- and 2-yr intervals, in contrast to once-burned 4-yr intervals, caused significantly higher NH_4^+-N concentrations for all strata in the fall of 1980. However, $N0_3^-$-N and total N were not significantly affected. The fall 1981 results indicated that plots not burned for 5 yr were almost identical to controls; therefore, we assume that had we been able to sample the controls in the fall of 1980, they would have been very similar to the 4-yr plots. Reburning the 4-yr plots seems to have caused a substantial surge in NH_4^+-N and NO_3^--N. This was true for both the spring and fall sampling dates. On the other hand, total N was not significantly affected.

DISCUSSION

Several mechanisms may be involved in causing increased soluble N following repeated burning. Both NH_4^+-N and NO_3^--N can be produced directly by burning (Christensen, 1973; DeBano et al., 1979; Mroz et al., 1980). In fact, in a separate study, we have observed that initial burning of heavy ponderosa pine fuels may immediately increase mineral soil NH_4^+-N by seven to 20-fold and $N0_3^-$-N by two- to fourfold (unpublished data, Covington and Sackett). However, this immediate increase does not account for all of the elevated NH_4^+-N and $N0_3^-$-N concentrations following burning. Ryan and Covington (1986) observed 80-fold increases in NH_4^+-N by early summer following the initial burns on our study area. Several other mechanisms may be involved in these later increases. Ammonium-N and $N0_3^-$-N may be leached into the mineral soil from the residual ash and forest floor. Microbial mineralization may be stimulated by improved soil moisture and temperature, as well as increases in the availability of other nutrients. Decreased uptake caused by root mortality might also cause higher mineral N; however, these effects should be localized under sites where logs and branches burn intensely. The substantial increases in $N0_3^-$-N following burning are most likely produced by increased nitrification rates resulting from the high NH_4^+-N availability, perhaps coupled with the denaturation of alielopathic nitrification inhibitors, which are known to be present in ponderosa pine litter and soils (Lodhi and Killingblrck, 1980). However, decreased nitrification might, also be expected because of selective mortality of nitrifying bacteria, which appear to be particularly sensitive to soil heating (Dunn and DeBano, 1977; Dunn et al., 1979).

No other data for comparing soil N among burning intervals are available for ponderosa pine. Several studies have found either total N decreases or increases with interval burning in other forest types, but none have examined NH_4^+-N or $N0_3^-$-N. Alban (1977) found no difference in total N among plots burned annually, biennially, every 6 to 9 yr, and controls in red pine (*Pinus resinosa* Ait.). Moehring et al. (1966) compared plots of mixed shortleaf pine (*Pinus echin*ata Mill.) and loblolly pine (*Pinus taeda* L.), which had been burned annually and biennially, with unburned plots. They found no difference in total N among any of the plots. However, Heyward and Barnette (1934) found significantly higher total N in the top 10 to 15 cm of soil on annually burned longleaf pine sites, in comparison to unburned sites. Wells (1971) also reported increases in total N after 20 yr of annual burning in the Coastal Plain of the southeastern United States: None of these researchers measured NH_4^+-N or $N0_3^-$-N.

Our results suggest that repeated burning is an important nutrient recycling pathway in southwestern ponderosa pine, and that effects on N concentrations vary with overstory conditions-the greatest response being under mature, sawtimber trees. In the absence of burning, forest litter steadily accumulates and mineral N concentrations remain low. Initial burning of these unnaturally heavy forest floor loads results in a major surge of available N for sawtimber and pole strata (Ryan and Covington, 1986). By yr 4 to 5, this increased N availability disappears. However, reburning at 1-, 2-, or 4-yr intervals can apparently be used to maintain periodic pulses of mineral N, not only for sawtimber and pole strata, but also for the sapling stratum. Since N has been shown to be limiting to productivity in many ponderosa pine forests (Powers, 1980; Cochran, 1979), and for ponderosa pine growing on similar soils near our study area in particular (Heidmann et al., 1979), we would anticipate that maintaining high N availability through periodic burning would benefit timber production in southwestern ponderosa pine. Furthermore, the increased understory production and improved forage quality following prescribed burns in southwestern ponderosa pine (Harris and Covington, 1983; Oswald and Covington, 1984) may be attributed, in part, to high N availability. Thus, herbage and forage production might also be improved by maintaining high N availability. However, our results, as well as those of Harris and Covington (1983) and Ryan and Covington (1986) indicate that the greatest responses are in the sawtimber stratum, with much lower responses in other strata. This is most likely a direct result of the much higher fuel loads under the sawtimber canopies.

In summary, our results suggest that controlled burning at frequent intervals can be used to increase mineral N in the mineral soil of southwestern ponderosa pine. Since there is approximately 1.6 X 106 kg/ha in the top 15 cm of the mineral soil (based on bulk density data) on our site, a difference in mineral N of 10 mg/kg represents an increase of 16 kg/ha of mineral N available in the surface soil of stands which are burned frequently. Since N availability has been shown to be limiting to productivity in ponderosa pine, these increases associated with repeated burning may be beneficial to both tree growth and understory production.

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