the NIPF population served most effectively by each agency or group in an effort to target their efforts, but should not restrict their efforts solely to a given audience or group. Further, additional attention should be paid to those owners without a history of using professional assistance to see if alternative programs could be developed to improve resource management on at least a portion of these holdings.

It is of paramount importance that professionals helping NIPF owners understand the objectives and interests of the owners. NIPF lands should not be looked at as tree factories. Timber management is compatible with the objectives of most owners, however, assistance programs will be more effective if they also help landowners accomplish their individual ownership/management objectives. □

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Nitrogen Fertilizer Response of Rocky Mountain Douglas-Fir by Geographic Area Across the Inland Northwest[1]

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ABSTRACT. Response to nitrogen fertilization treatments in Rocky Mountain Douglas-fir (Pseudotsuga menziesii var. glauca) *differed significantly among geographic regions within the inland northwest. Gross basal area and volume growth on fertilized plots were significantly greater than growth on controls for all geographic regions, but only in northern Idaho and central Washington was gross response significantly greater on 400 lb/ac N plots than on 200 lb N plots. Net basal area and volume growth on treated plots in Montana, central Idaho, and northeast Oregon were not significantly greater than the controls for either nitrogen treatment. Analysis of 2-year periodic basal area increment indicated that, while response did decline through time, treated plots continued to produce more gross growth than control plots 6 years after treatment. Similar operational nitrogen treatments applied to the Douglas-fir population sampled in this study should produce gross responses exceeding 10% after 6 years three out of four times.*

West. J. Appl. For. 6(4):94–98.

In 1980 a group of forestland management organizations formed the Intermountain Forest Tree Nutrition Cooperative (IFTNC) to study the nutrition of forest tree species of the inland northwest of the United States. Initial efforts concentrated on studying the effect of nitrogen (N) fertilization on Rocky Mountain Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), the tree species of greatest interest in the area due to its ubiquity and a lack of response information. To accomplish this task, the IFTNC established a series of nitrogen fertilizer trials throughout the area. The study was designed to test the hypothesis that nitrogen limits Rocky Mountain Douglas-fir growth in the inland northwest. Previously, moisture has been considered to be the primary factor limiting tree growth in the region (Haig et al. 1941).

METHODS

Study Area, Population, and Design

The inland northwest region studied is a large, ecologically diverse area stretching from the eastern slopes of the Cascade Mountains in Washington to the western slopes of the Rocky Mountains in Montana and from the Canadian border in the north to the Snake River plain in southern Idaho and adjacent Oregon. From 1980 to 1982, the IFTNC established 94 fertilizer trials (installations) in this area. By design, these installations fall in six geographic regions: central Washington, northeast Washington, northern Idaho, western Montana, central Idaho, and northeast Oregon.

Installations were located in second-growth, even-aged, managed Douglas-fir stands. Most stands had been thinned 5 to 12 years previously; a few stands were unthinned, but naturally well-spaced. Stands were selected to cover a range of stand densities, tree ages and sizes, and site productivities (Table 1). The stands are dominated by Douglas-fir; on average, 87% of the basal area was Douglas-fir, and all but one stand was comprised of at least 57% Douglas-fir. Other species contributing substantial basal area include ponderosa pine (*Pinus ponderosa*), lodgepole pine (*P. contorta*), western larch (*Larix occidentalis*), and grand fir (*Abies grandis*). Generally, the range of stand mensurational characteristics was similar among regions; however, site index did vary among the regions.

Each installation consists of six square plots from 0.1 to 0.2 ac in size. The plots each contain at least ten Douglas-fir sample trees and were selected to minimize among-plot variation in terrain, vegetation composition, tree stocking, and tree size. Plots were grouped into two blocks of three plots based on similarity of these features to further reduce variaton. Three

[1] This research was supported by the Intermountain Forest Tree Nutrition Cooperative, located at the College of Forestry, Wildlife and Range Sciences, University of Idaho. College of FWR Experiment Station contribution no. 599.

Table 1. Averages and ranges for site and stand characteristics across the 94 fertilizer installations at the initiation of the experiment

Characteristic	Mean	Min.	Max.
Elevation (ft)	3580	1500	5900
DF site index[1] (ft @ 50 yr)	69	41	97
Age (yr)	65	27	100
Basal area in DF (%)	87.3	27.7	100.0
Quadratic mean diameter (in.)	10.3	6.1	16.7
Trees/ac	267	103	702
Basal area (ft²/ac)	141	48	272
Total volume (ft³/ac)	3695	740	8320

[1] Monserud (1984).

fertilizer treatments—0, 200, and 400 lb/ac of nitrogen—were randomly assigned to the plots within each block. Nitrogen in the form of urea was applied in the late fall utilizing handheld spreaders. All fertilized plots were surrounded by at least a treated 25-ft buffer strip to reduce edge effects.

Data Collection and Compilation

All live plot trees were tagged and measured for heights and diameters at the time of treatment. Every 2 years diameters were remeasured on all trees, and any incidence of damage or mortality along with probable cause was noted. Heights were remeasured 4 years after treatment on all trees. At 6 years, heights were measured on a stratified random sample of plot trees. Six-year heights for unmeasured trees were estimated using plot-specific regression equations for height growth for years 5 and 6 based on 4-year height and diameter growth in years 5 and 6. (Average S.E.E. of these 270 equations was 0.45 ft.) Tree total volumes were estimated using regional species-specific volume equations (Wykoff et al. 1982). Basal areas and total volumes were summed over all trees (not just Douglas-fir) to obtain plot totals.

Statistical Analysis

Plots within an installation were selected to be similar; therefore differences in site index, age, etc., within an installation were slight. However, some within-installation initial density differences were present; thus, analysis of covariance was used to remove the effect of differences in density on plot growth.

Fertilizer effects on growth were estimated with a split-plot analysis of covariance model; in this study, whole plots correspond to installations, and split plots are fertilizer treatment plots. The particular model fit was (after Federer 1955):

$$\begin{aligned} Y_{hijk} = {} & \mu + R_h + \beta_1 X_{hi\cdot} + \beta_2 X^2_{hi\cdot} \\ & + I_{i(h)} + B_{j(ih)} + F_k + RF_{hk} \\ & + \beta_3 X_{hijk} + \beta_4 X^2 h_{ijk} \\ & + \beta_3 F_k X_{hijk} + \beta_4 F_k X^2_{hijk} \\ & + e_{hijk} \end{aligned} \quad (1)$$

where Y_{hijk} is the 6-year growth (net and gross basal area and volume) for the split plot (i.e., the kth fertilizer treatment in the jth block of the ith installation within the hth region), μ is the overall mean effect, R_h is the effect due to the hth region, $I_{i(h)}$ is a whole-plot random effect due to the ith installation within the hth region, $B_{j(ih)}$ is a nested random effect due to the jth block of the ith installation within the hth region, F_k is the split-plot effect due to the kth fertilizer treatment, RF_{hk} is the interaction effect between region and fertilizer, X_{hijk} is the basal area per acre at the start of the experiment for the split plot, $X_{hi\cdot}$ is the installation (whole plot) initial basal area per acre, β_1 and β_2 are coefficients for initial basal area influences on whole-plot growth, β_3 and β_4 are coefficients for initial basal area influences on split-plot growth, $\beta_3 F_k$ and $\beta_4 F_k$ are coefficients for the influence of the interaction of fertilizer treatment with initial basal area on split-plot growth, and e_{hijk} is a random split-plot error effect. Multivariate analysis of covariance for net and gross basal area and volume growth indicated that the interaction between region and fertilizer treatment and between fertilizer treatment and initial basal area and the quadratic initial basal area term were all highly significant ($P \leq 0.0001$).

Parameter estimates, adjusted means, and contrasts of interest for the above model were obtained using the general linear models procedure (PROC GLM) of the Statistical Analysis System (SAS Institute Inc. 1985). Coefficients obtained by fitting Equation (1) were used to adjust treatment plot growth rates for differences in initial basal area. Growth response to fertilization was then calculated by subtracting adjusted growth on control plots from similar growth on fertilized plots. These adjusted fertilizer response rates are the values presented throughout the rest of this paper. For individual installations, growth was adjusted to the average initial basal area for each installation; for comparisons across regions, growth was adjusted to 150 ft²/ac initial basal area (a typical value close to the mean density).

Duration of response was analyzed using a repeated measures analysis of covariance utilizing the REPEATED option of PROC GLM in SAS (SAS Institute Inc. 1985). Tests of sphericity

Table 2. Six-year average response in gross total volume by region and treatment. Values in parentheses represent significance levels for tests that the treatment contrasts are equal to zero.

		Gross volume			
		Growth		Response	
Region	Treatment	ft³/ac	Contrast	ft³/ac	%
Northern Idaho	Control	1310			
	200 # N	1517	200 − 0	207 (0.001)	15.8
	400 # N	1608	400 − 0	298 (0.001)	22.7
			400 − 200	91 (0.005)	6.0
Montana	Control	689			
	200 # N	793	200 − 0	104 (0.002)	15.1
	400 # N	792	400 − 0	103 (0.003)	15.0
			400 − 200	−1 (0.977)	−0.1
Central Idaho	Control	924			
	200 # N	1048	200 − 0	124 (0.001)	13.4
	400 # N	1058	400 − 0	134 (0.001)	14.5
			400 − 200	9 (0.807)	0.9
Northeast Oregon	Control	802			
	200 # N	883	200 − 0	81 (0.082)	10.1
	400 # N	887	400 − 0	85 (0.089)	10.5
			400 − 200	3 (0.945)	0.4
Central Washington	Control	962			
	200 # N	1201	200 − 0	239 (0.001)	24.9
	400 # N	1333	400 − 0	371 (0.001)	38.6
			400 − 200	131 (0.001)	10.9
Northeast Washington	Control	1027			
	200 # N	1154	200 − 0	127 (0.001)	12.5
	400 # N	1156	400 − 0	129 (0.001)	12.6
			400 − 200	3 (0.940)	0.2
Overall	Control	977			
	200 # N	1134	200 − 0	157 (0.001)	16.1
	400 # N	1181	400 − 0	204 (0.001)	20.9
			400 − 200	47 (0.009)	4.1

indicated that a univariate split-split-plot analysis of covariance model was appropriate for the data, where fertilizer split plots were further split based on time period. As above, the model parameter estimates were used to adjust plot growth values for within-installation differences in initial basal area.

RESULTS

Average Growth Response

Analysis of growth data for the 6 years following treatment shows that trees do respond to nitrogen fertilization. Average gross volume growth (treatment means) and response to the nitrogen treatments (contrasts between treatment means) are given in Table 2. Growth differences between treated and control plots are considered to be fertilizer response while those between 400 and 200 lb/ac N plots indicate any response associated with increasing the fertilization rate. Tests on the treatment contrasts indicated that 6-year gross volume growth on both the 200 and 400 lb/ac nitrogen treatments was significantly greater than that on controls for all geographic regions; significance levels for the tests are shown within parentheses in the table. Across all regions, growth increased by 16.1% and 20.9% on plots fertilized with 200 lb/ac and 400 lb/ac N, respectively. In northern Idaho and central Washington, treated plots grew over 200 ft³/ac more than control plots in 6 years. In addition, trees on 400 lb plots grew more than those on 200 lb plots, but not across all regions: in northern Idaho and central Washington the higher N rate increased growth significantly, but significant increases were not obtained in any other region.

The results are different for net volume increment (Table 3). While most regions show a positive net growth response to N fertilization, the magnitude is less than gross response, indicating an increase in mortality rates with N treatment. Mortality increases were sufficient to produce negative net response in northeast Oregon for both treatment rates and in northeast Washington for the 400 lb rate. The variability of the results is also larger due to variable mortality. Thus, net volume response is nonsignificant in Montana and central Idaho. Central Washington showed the greatest net volume growth response to both nitrogen treatments (200 lb/ac N = 201 ft³, 21.8%; 400 lb/ac N = 319 ft³, 34.5%). The net volume growth for the 400 lb/ac treatment is significantly greater than for the 200 lb treatment in northern Idaho and central Washington.

Duration of Response

Duration of fertilizer response was examined by analyzing the change in periodic basal area increments through time; since height measurements had not been taken every 2 years, periodic volume growth estimates were not available. Gross and net basal area increments for the first, second, and third 2-year periods are compared in Table 4; values are averages by treatment and region adjusted to a common initial basal area of 150 ft²/ac.

Gross basal area response declined for each successive 2-year period in all regions. In years 1 to 2 and 3 to 4 all regions showed significant ($P < 0.1$) positive response to fertilization for both 200 and 400 lb/ac N treatments. In years 5 to 6, although all regions

Table 3. Six-year average response in net total volume by region and treatment. Values in parentheses represent significance levels for tests that the treatment contrasts are equal to zero.

		Net volume			
		Growth		Response	
Region	Treatment	ft³/ac	Contrast	ft³/ac	%
Northern Idaho	Control	1304			
	200 # N	1423	200 − 0	119 (0.066)	9.1
	400 # N	1529	400 − 0	225 (0.001)	17.3
			400 − 200	106 (0.102)	7.4
Montana	Control	625			
	200 # N	668	200 − 0	43 (0.529)	6 8
	400 # N	658	400 − 0	32 (0.633)	5.2
			400 − 200	−10 (0.880)	−1.5
Central Idaho	Control	889			
	200 # N	982	200 − 0	94 (0.217)	10.5
	400 # N	970	400 − 0	81 (0.281)	9.1
			400 − 200	−12 (0.870)	−1.3
Northeast Oregon	Control	705			
	200 # N	648	200 − 0	−57 (0.537)	−8.1
	400 # N	664	400 − 0	−41 (0.681)	−5.8
			400 − 200	17 (0.866)	2.6
Central Washington	Control	923			
	200 # N	1124	200 − 0	201 (0.002)	21.8
	400 # N	1242	400 − 0	319 (0.001)	34 5
			400 − 200	118 (0.061)	10.5
Northeast Washington	Control	905			
	200 # N	1036	200 − 0	131 (0.53)	14 5
	400 # N	893	400 − 0	−12 (0.861)	−1.3
			400 − 200	−143 (0.033)	−13.8
Overall	Control	920			
	200 # N	1024	200 − 0	104 (0.003)	11 3
	400 # N	1041	400 − 0	121 (0.001)	13.2
			400 − 200	17 (0.624)	1 7

Table 4. Average gross and net basal area growth for each two-year period by region and treatment.

		Periodic basal area increment (ft²/ac · yr)					
		Gross BAI			Net BAI		
		Years			Years		
Region	Treatment	1–2	3–4	5–6	1–2	3–4	5–6
Northern Idaho	Control	5.9	5.3	5.6	6.3	4.9	5.0
	200 # N	7.7	6.5	5.9	7.5	5.3	5.1
	400 # N	8.1	7.2	6.6	7.8	5.6	6.3
Montana	Control	3.6	2.9	2.8	3.3	2.5	2.4
	200 # N	4.3	3.5	3.0	3.6	2.3	2.3
	400 # N	4.3	3.4	3.0	4.2	1.6	2.3
Central Idaho	Control	4.5	4.7	3.5	4.4	4.6	3.2
	200 # N	5.4	5.2	3.8	5.2	5.3	3.0
	400 # N	5.6	5.2	3.8	5.5	4.7	3.0
Northeast Oregon	Control	3.7	3.7	2.7	3.4	3.0	1.7
	200 # N	4.3	4.1	3.0	3.9	2.8	0.8
	400 # N	4.7	4.2	3.1	4.0	3.0	1.5
Central Washington	Control	4.4	4.2	3.6	4.3	4.2	3.1
	200 # N	5.9	5.3	4.2	5.7	5.8	3.6
	400 # N	6.6	5.9	4.6	6.4	5.8	3.6
Northeast Washington	Control	5.0	4.6	3.7	4.8	3.4	2.8
	200 # N	5.9	5.2	4.0	5.7	4.1	2.9
	400 # N	6.1	5.2	4.1	5.9	2.3	2.1
Overall	Control	4.6	4.3	3.8	4.5	3.8	3.2
	200 # N	5.8	5.1	4.1	5.5	4.3	3.4
	400 # N	6.1	5.3	4.4	5.8	4.0	3.4

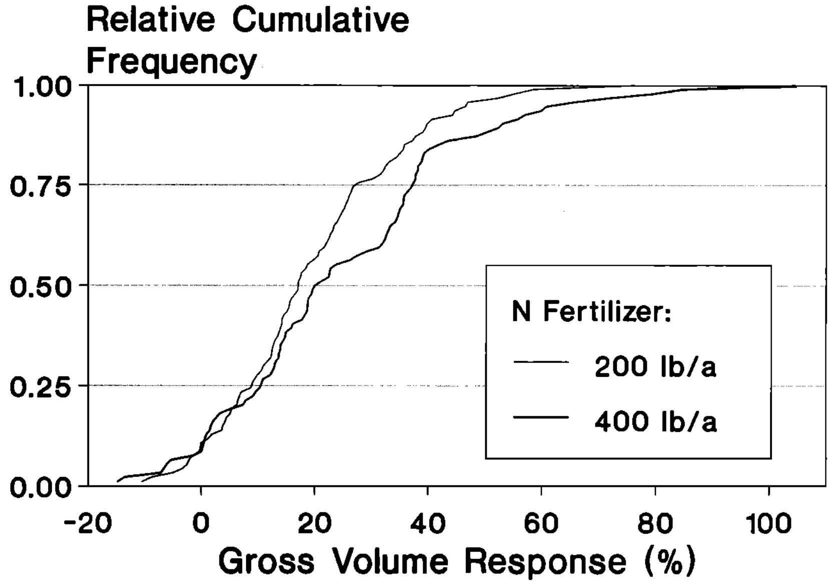

Figure 1. The relative cumulative frequency distribution of 6-year relative growth response (percent) across all regions by fertilizer treatment. Values on the vertical axis are the proportions of the entire sample that were less than or equal to particular response values on the horizontal axis.

showed a positive response, the 200 lb/ac N response was only statistically significant ($P < 0.1$) in northern Idaho and central Washington. Gross basal area growth on the 400 lb/ac N treatment continued to be significantly greater ($P < 0.1$) than the controls during years 5 to 6 across all regions, except for northeast Oregon ($P = 0.168$). Northern Idaho and central Washington were the only regions to show a significant ($P < 0.1$) increase in gross growth when the application rate increased from 200 to 400 lb/ac.

The decline in net basal area response to the fertilizer treatments is even more pronounced than for gross basal area. The only treatment in any region that produced a significant net basal area response for years 5 and 6 was the 400 lb/ac nitrogen treatment in northern Idaho ($P = 0.016$). Mortality is variable by treatment, region, and time period, and this variation contributes to the lack of significance of the treatment effect for net basal area.

Response Variation

The variation in treatment response across the entire experiment is shown in Figure 1. Within-installation growth differences attributable to differences in initial stand density have been removed using Equation (1). Values are presented in an empirical cumulative distribution function: the vertical axis indicates the proportion of all installations that responded less than or equal to a particular gross volume response value shown on the horizontal axis. Response is expressed as a percentage of control plot growth. For example, of all the 200 lb/ac treatments approximately half of the stands responded less than 15% and about 10% responded more than 45%. Additional information about regional response variation is provided in Table 5. Values given are the minimum, median, maximum, and inner quartiles of gross volume response expressed relative to control plot growth. In every region some installations responded well to N fertilization while others responded negligibly or even negatively.

DISCUSSION

Nitrogen fertilization did, on the average, significantly increase basal area and volume growth over a 6-year period following treatment, clearly showing that nitrogen limits Rocky Mountain Douglas-fir growth in the study region, at least during those parts of the growing season when moisture is not limiting. While overall response to nitrogen fertilization declined for each successive 2-year period after treatment, so did average density adjusted control plot growth. Both net and gross basal area increments for the untreated control plots were lowest in years 5 and 6 for all geographic regions except northern Idaho. For Montana, central Washington, and northeast Washington, there have been successive declines in control plots growth for each 2-year period. This decline in growth rate of the control plots is likely associated with increasingly dry climatic conditions, particularly during years 5 and 6; this may explain some of the reduction in nitrogen response in those years.

Average responses by region and treatment are useful for making general comparisons and conclusions, but, since we intentionally selected installations to cover a broad range of site and stand conditions, it would be unlikely that all installations would respond to nitrogen fertilization. Results from coastal Douglas-fir suggest that differences in site quality as measured by site index explain some of the variation in nitrogen fertilizaton response, with greater response occurring on sites with lower site index (Heath and Chappell 1989, RFNRP 1989). However, in our study, regional fertilization response does not correspond to average regional productivity expressed as either nonfertilized stand volume growth or average site index (Table 6). Growth rates and site indexes are in general agreement across the study area; with the exception of central Idaho, all regions rank similarly for growth rate and site index. In contrast, fertilizer response, when expressed relative to control plot growth, shows little variation among the regions and no association to either average growth rate or site index. Central Washington, the only area with substantially different relative response, is intermediate in both site index and growth rate. This suggests that different factors not directly re-

Table 5. Selected percentiles of the relative gross volume response distribution by region and treatment.

	Nitrogen treatment									
	200 # N					400 # N				
	Percentile					Percentile				
Region	Min.	25%	50%	75%	Max.	Min.	25%	50%	75%	Max.
Northern Idaho	−5.0	6.4	12.9	34.3	40.6	−7.1	12.1	23.9	37.8	50.3
Montana	−10.5	5.6	22.9	26.4	55.1	−13.5	3.1	19.0	38.4	71.5
Central Idaho	−8.6	7.8	13.3	33.5	52.3	−6.1	9.8	22.6	34.7	37.8
Northeast Oregon	−2.1	1.1	15.1	20.9	24.8	−14.7	3.5	9.5	27.3	38.2
Central Washington	−0.1	14.4	25.5	39.5	74.7	0.0	21.1	48.5	60.7	104.6
Northeast Washington	−3.3	6.3	17.0	23.0	33.2	−1.5	6.7	14.4	24.4	39.3
Overall	−10.5	8.8	17.0	28.4	74.7	−14.7	10.5	20.6	37.5	104.6

Table 6. Average adjusted total gross volume growth, site index, and nitrogen fertilization response by geographic region.[1]

Region	Six-year vol. growth (ft^3/ac)	Site index	% Response 200N	400N
Northern Idaho	1310	83	15.8	22.7
Montana	689	63	15.1	15.0
Central Idaho	924	57	13.4	14.5
Northeast Oregon	802	65	10.1	10.5
Central Washington	962	68	24.9	38.6
Northeast Washington	1027	70	12.5	12.6

[1] Average growth is adjusted to a common initial basal area of 150 ft^2/ac using Equation (1).

lated to site productivity effect nitrogen fertilization response. Miles and Powers (1988), working in California, also found that site index alone was not a strong predictor of N fertilization response and suggested that differences in soil total available water capacity for a given site index helped explain fertilization response differences. This may also be true for our study. We are currently investigating reasons for lack of response for some installations. Preliminary results suggest that high levels of available N or low availability of other nutrients on certain soils may explain lack of N fertilization response.

If we were able to avoid fertilizing stands that respond less than average (or the median in this example), then the 75th percentile of the response distribution would be the new median response to nitrogen treatments. The 75th percentile response for the 200 lb/ac N treatments range from a low of 20.9% in northeast Oregon to a high of 39.5% in central Washington. For the 400 lb/ac N treatment, the range was from 27.3% in northeastern Oregon to a high of 60.7% in central Washington.

In summary, these results provide a better understanding of the nutritional status of Douglas-fir in the inland northwest region. Response of Douglas-fir stands to nitrogen fertilization in a wide variety of site conditions has been quantified, and nitrogen has been shown to limit growth for most stands in the region. Average gross response is significant for all regions, but variation among stands is high. Some stands do not show per acre growth response to nitrogen fertilization while other stands respond substantially after 6 years. The 400 lb N treatment produces more growth response than the 200 lb treatment in two regions. Higher average mortality rates for fertilized plots reduced average growth and increased variability; thus, average net nitrogen response is not statistically significant for some geographic regions. However, as Shafii et al. (1989) showed, higher mortality rates in fertilized stands are not necessarily bad, particularly if the mortality is concentrated in smaller size classes in dense stands; the long term result is a stand with similar volume but more big trees. Even so, over a short time period, the death of a few small trees can cause negative stand growth response to fertilization.

Nitrogen fertilization seems to be a viable intermediate silvicultural treatment for many Douglas-fir stands in the region; for example, about 25% of the Douglas-fir stands sampled showed response exceeding 28% after 6 years. As substantial acreages with stand and site characteristics similar to those in Table 1 exist in the region, the potential for significant volume increases is obvious. Given increasing demands to produce more timber from a decreasing land base, nitrogen fertilization is a treatment that usually produces substantial volume increases in a relatively short time period. □

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