RESPONSE TO FERTILISER IN A PINUS RADIATA PLANTATION. 1: ABOVE-GROUND BIOMASS AND WOOD DENSITY

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ABSTRACT

Sample trees of 10-year-old **Pinus radiata** D. Don were removed from untreated plots and from plots which had been treated with fertiliser shortly after planting. Regression equations relating the logarithm of each biomass component to the logarithm of tree basal area were fitted for stem wood, stem bark, live branches. and live needles. Treatment effects were significant only for live-needle biomass, with unfertilised trees having greater needle biomass per unit of basal area than fertilised trees.

The regression equations were solved for all trees and the biomass data converted to an area basis. Total above-ground biomass increased with increasing level of applied phosphate, up to 67 kg P/ha. Application of phosphorus resulted in significant increases in all above-ground components including stem wood, stem bark, live branches, and live needles. There was no additional response to nitrogen and potassium applied in combination with phosphorus at any level up to 800 kg N/ha.

A large response to phosphatic fertiliser occurred in diameter growth, with only a minor response in height growth. This caused a significant increase in the average taper of the fertilised trees. The pronounced response in growth did not result in any significant change in wood density.

The partitioning of the above-ground biomass components between crown and stem did not differ substantially between fertilised and unfertilised trees, and this appeared to be related to the lack of a response in height growth. Stem wood biomass in **P. radiata** stands can be determined from simple measurements of height and basal area.

Keywords: biomass; wood density; nitrogen; phosphorus; potassium.

INTRODUCTION

The need to apply phosphatic fertilisers to maintain health in many *Pinus radiata* plantations in Australia has been recognised for some 50 years (Kessel & Stoate 1936) and the subject has received a great deal of attention during this time (*see* review by Raupach 1967). Despite the considerable literature on both biomass components and fertiliser responses in *P. radiata,* there are relatively few data comparing biomass components in fertilised and unfertilised stands (Waring 1973; Flinn *et al.* 1982).

Changes in the relative proportions of above-ground biomass components of a forest occur as storage and structural organs become larger with age. Detailed studies have been conducted in Australia and New Zealand on *P. radiata* stands between the ages of 2 and 22 years. Forrest & Ovington (1970) noted that needle biomass in a 3-year-old stand represented 45% of total above-ground biomass, but this had fallen to 8% in a 12-year-old stand. Needle biomass in a 2-year-old stand represented 51% of the total above-ground biomass but only 3% in a 22-year-old stand (Madgwick *et al.* 1977). Applications of fertiliser to recently established stands growing on nutrient-poor soils, frequently lead to increases in growth and a reduction in the time taken to close canopy. It might be expected that such increases in growth rate would lead to changes in the proportions of the above-ground components similar to those noted during the aging process, but this has received little study.

An increase in the standing biomass of foliage has generally been associated with growth responses to fertiliser reported for a number of pine species (*see* Madgwick *et al.* 1977). Whilst there is an increase in the absolute amount of foliage after fertiliser application, the proportion of the above-ground biomass found in the foliage may not change. Trees grown in lysimeters with access to additional nutrients had larger branches which produced considerably greater quantities of foliage than trees under nutrient stress (Will & Hodgkiss 1977), but examination of these data showed only minor differences in the proportion of the above-ground biomass which occurred in foliage. The above-ground biomass of a *P. radiata* stand in Victoria also increased with increasing rates of broadcast superphosphate but the proportions of each component were similar for the three treatments examined (Flinn *et al.* 1982).

Data from some studies have shown that increased growth of *P. radiata* as a result of fertiliser applications has also caused decreases in wood density (Rudman & McKinnell 1970; Cown & McConchie 1981). Other studies have found little or no difference in wood density following responses in growth to fertiliser (Fielding & Brown 1961; Gentle & Humphreys 1968).

The experiment reported in this paper was planted in 1971, and given a range of nutrient treatments shortly after establishment. Earlier measurements demonstrated that there had been substantial responses in growth to applied phosphorus and a rate of 67 kg P/ha was found to be economically attractive (Cromer *et al.* 1977; Dargavel & Cromer 1979). There had also been a substantial decrease in wood density in fertilised trees when compared with unfertilised trees at 4 years of age (Nelson *et al.* 1980). The experiment had been measured several times during the first 10 years and, in order to obtain additional information on the response in biomass and wood density of *P. radiata* to fertiliser, a detailed assessment of above-ground biomass was made at 10

years of age. The nature of the responses is examined in this paper, and the effect of fertiliser treatment on nutrient accumulation and partitioning is examined in the second paper in this series (Cromer *et al.* 1985).

MATERIALS AND METHODS

Field

The experiment was established in winter 1971 at a site 13 km south-east of Traralgon, Victoria, Australia (38° 16'S, 146° 40'E). The site had previously carried a stand of *P. radiata* and was ploughed and mounded prior to planting with *P. radiata* at a nominal stocking of 1900 stems/ha (3 × 1.75 m). The site was at an elevation of 100 m a.s.l. and received a mean annual rainfall of approximately 700 mm. Weed growth was controlled with pre-emergent herbicides applied at planting and 1 year later to four of the five blocks of the experiment. Data presented in this paper refer only to the four blocks in which weeds were controlled.

Each block contained 12 plots, each of which was 15 × 13 m with an internal plot of 9 × 9 m for measurement purposes. Three of the 12 plots were unfertilised controls (P_0), the other nine were fertilised with one of three nutrient combinations (phosphorus alone, nitrogen + phosphorus, or nitrogen + phosphorus + potassium with trace elements) at one of three application rates (Table 1). No response to potassium with trace elements was recorded at any stage so details of the trace elements have not been included. Fertiliser was broadcast over the mounds in which the seedlings were planted, and so was concentrated on about half the area. To avoid toxic levels of fertiliser (particularly nitrogen) being applied to seedlings, the heavier rates were split into a number of applications. All treatments apart from the control received the equivalent of Rate 1 three months after planting (August 1971). The remainder of the fertiliser in Rate 2 plots was applied in January 1972. The remainder of the fertiliser in Rate 3 plots was divided into four equal amounts and applied at 6-monthly intervals from January 1972 till July 1973.

TABLE 1—Fertiliser treatments applied to the experiment during the first 30 months

Fertiliser type	Fertiliser rate			
	Nil	1	2	3
Symbols used for treatments				
Control	P_0			
Phosphorus (P)		P_1	P_2	P_3
Nitrogen (N) + P		P_1N_1	P_2N_2	P_3N_3
Potassium (K) + NP		$P_1N_1K_1$	$P_2N_2K_2$	$P_3N_3K_3$
Amounts of fertiliser applied (kg/ha)				
P as double superphosphate		22	67	202
N as urea		90	269	807
K as potassium sulphate		26	77	232

Trees in each internal plot were measured a number of times between 1971 and 1981 and a few of these data have been reported by Cromer et al. (1977) and Dargavel & Cromer (1979). Diameters at breast height over bark (d.b.h.o.b.) of all trees and heights of about one-third of them were measured when the trees were aged 10 years. Plot values of predominant height (tallest 30 stems/ha), mean diameter, basal area, and merchantable volume were calculated on the Management Information System of APM Forests Pty Ltd (Dargavel et al. 1975).

Results from these measurements showed no additional growth response to fertiliser application above 67 kg P/ha (P_2) so samples for biomass estimation were taken from the P_0 and P_2 treatments only. Sample trees were taken from each of the three nutrient combinations within the P_2 application rate (P_2, N_2P_2, and $N_2P_2K_2$). Above-ground biomass was estimated from five sample trees in each of the four treatments examined. From each treatment, the trees from the four blocks were divided equally into five diameter classes and one sample tree was selected at random from each class. All dead branches were cut from the tree and weighed in the field and a sub-sample was weighed for retention. The tree was cut at ground level and total height and height to the base of the green crown were measured. The green crown was marked into five sections of equal length and two sample branches were removed at random from each section, weighed, and taken to the laboratory. The remaining green branches from each section were cut, weighed, and discarded.

Each stem was cut into 10 billets of equal length, diameter over and under bark was measured, and a disc was cut from the large end of the billet. Green weights of both billets and discs were measured in the field and the discs were taken to the laboratory. On the same day the volume of each wood disc was determined by the mass displacement of water. Needles were removed from each sample branch and separated into age-classes. Sub-samples of all components including stem wood, stem bark, dead branches, live branches, dead needles, live needles, and female cones were taken to the laboratory and dried at 75°C to constant weight. Oven-dry weight for each component was determined from the ratio of green weight to dry weight measured on the sub-samples.

The wood discs taken at 20% and 50% of stem height were examined using X-ray densitometry. Samples were cut from each disc from pith to bark and prepared by machining to 7.00 mm ($\pm$ 0.05 mm) in the grain direction at a stabilised moisture content of 8%. These sub-sections were placed on X-ray film and irradiated on the transverse face to give an image whose optical density at any point was related to the density of the sub-section at the corresponding point on the sub-section. Optical density of the X-ray images was determined by scanning at 100-μm intervals with a Joyce Loebl Autodensidater Mark III, with an internal digitiser. Maximum, minimum, and mean density, as well as a density profile, were determined for each ring.

Biomass Estimation

Regression equations relating the logarithm of each biomass component to the logarithm of tree basal area were fitted for stem wood, stem bark, live branches, and needles for each treatment using GENSTAT (Genstat Manual 1977). The equations were solved to determine the biomass components of each tree in each plot; the

components were then summed for all trees in each plot and converted to mass per unit area. Estimates were corrected for the systematic bias of the logarithmic transformation (Baskerville 1972).

The correlations between tree basal area and the dead branch, dead needle, and female cone components were not high ($r^2 < 0.5$), so these components were estimated by taking the mean of the sample trees in each treatment and multiplying by the mean number of trees per hectare for that treatment.

RESULTS

There was no significant response to fertiliser type for any of the stand characteristics so these data are not presented. Differences between unfertilised and fertilised trees were all significant however.

The major responses were to phosphorus, and these responses were examined by averaging the stand characteristics for each fertiliser "type" corresponding to a particular application rate of phosphorus (Fig. 1). Phosphatic fertiliser had a minor effect on predominant height, with a significant difference ($p < 0.01$) only between P_0 and the three rates combined. Mean diameter increased from 11.2 cm in P_0 plots to 15.4 cm in P_2 plots, but there was no further significant increase in P_3 plots. Basal area increased from 17.7 m^2/ha in P_0 plots to 32.0 m^2/ha in P_2 plots but, as with diameter, there was no further significant increase in P_3 plots. Merchantable volume followed a similar pattern of response to increase in phosphatic fertiliser ($p < 0.01$), from 71.4 m^3/ha in P_0 plots to a maximum of 151.2 m^3/ha in P_2 plots.

Since phosphatic fertiliser had a large and significant ($p < 0.001$) effect on diameter but only a small effect on height, the form of the trees changed as a result of phosphorus
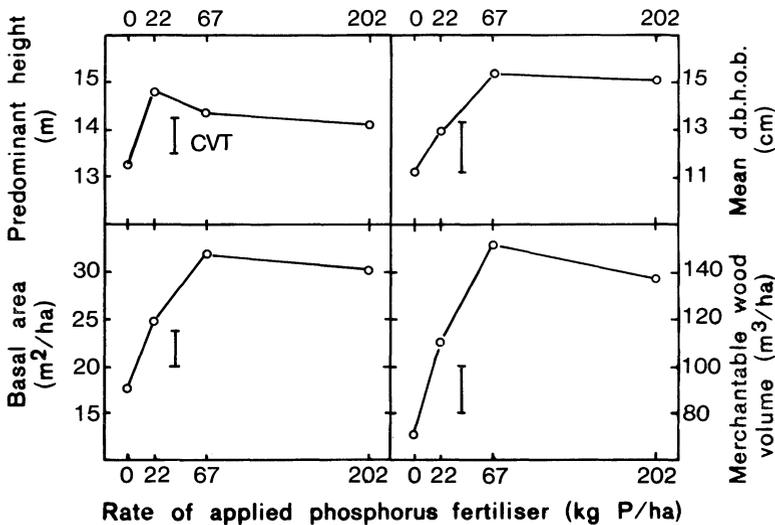
FIG. 1—Relationship between stand characteristics of **P. radiata** aged 10 years and the rate of phosphorus fertiliser applied shortly after planting.

application. Average taper, expressed as diameter at breast height per unit of height, increased from 1.10 cm/m in P_0 plots to 1.12 cm/m in P_2 plots (p <0.01).

Regression equations for the biomass components derived from the 20 sample trees are shown in Table 2; variance accounted for in all equations exceeded 90%. Basal area was the most effective independent variable and height did not significantly improve the fit for any of the components. Treatment effects were significant (p < 0.05) only for live needle biomass, with P_0 having a greater mass per unit of basal area (over bark) than fertilised trees. One fertilised tree was found to have a very high needle biomass compared with other fertilised trees and it was omitted from the calculation when it was found to have been situated in a gap surrounded by trees of below-average size.

TABLE 2—Regression equations* for components of sample trees of **Pinus radiata** aged 10 years

y		a	b	Var.
Stem wood volume (m³)		1.164	–8.389	97.5
Stem wood biomass (g)		1.123	4.768	97.9
Stem bark biomass (g)		1.056	3.279	92.4
Live branch biomass (g)		1.244	2.399	90.3
Live needle biomass (g)	P_0	1.433	1.653	91.6
	P_2	1.433	1.076	91.6
Total biomass (g)		1.127	5.142	97.8

* The equations took the form: $\ln y = a (\ln x) + b$
  where y   = component
       x   = basal area over bark at breast height (cm²)
      Var. = variance accounted for by the equation (%)

Components of the above-ground biomass were calculated from the regression equations as described previously and are shown against level of phosphorus fertiliser in Fig. 2. As there was a significant treatment effect for live needle biomass, the figure for P_1 is less reliable than those for P_0 and P_2 from which the sample trees were taken. There were no significant differences in growth between P_2 and P_3, and so the data for P_3 should be reliable. Stem wood, stem bark, live branch, and live needle biomass all increased with increasing rate up to P_2. Above-ground biomass of these live components totalled 100 t/ha in P_2 plots compared with 63 t/ha in P_0 plots. There were considerably more dead needles and dead branches in P_2 plots and with these included the comparison was 117 and 63 t/ha in P_2 and P_0 plots respectively.

Stocking at the time of measurement in the unfertilised plots was 1630 stems/ha compared with an average of 1688 stems/ha in the fertilised plots. Trees in the unfertilised plots had very thin crowns and had not "closed canopy" in the conventional sense at the time of measurement. Since the fertilised trees had grown faster and had closed canopy, there was a change in the proportion of stem which supported live branches, with the green crown covering only 78% of the stem length in fertilised trees compared with 89% in unfertilised trees (p <0.05).
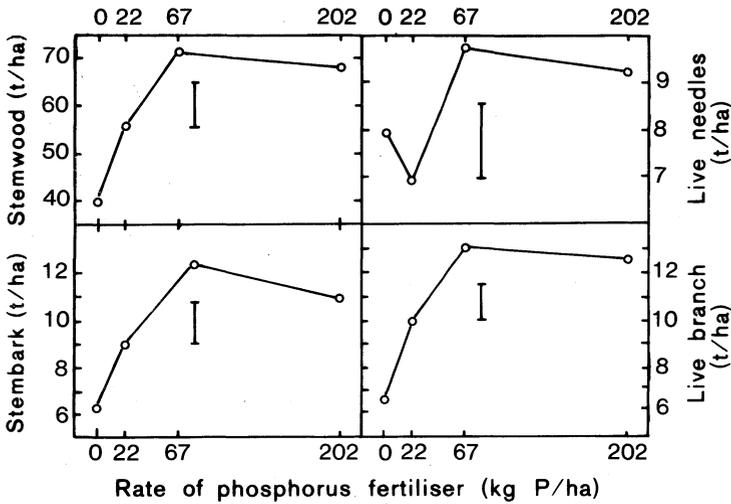
FIG. 2—Relationship between the components of the above-ground biomass of
P. radiata aged 10 years and the rate of phosphorus applied shortly after
planting.

A comparison of minimum, mean, and maximum wood density at 20% of tree
height over the last 6 years of the experiment is presented in Fig. 3. No significant
differences were detected between treatments for minimum, mean, or maximum wood
density for any year between 1976 and 1981. An independent estimate of average wood
density, obtained from over-all stem wood biomass and stem wood volume also indicated
the average density in unfertilised trees of 0.43 g/cm³ did not differ from that in
fertilised trees (0.42 g/cm³).
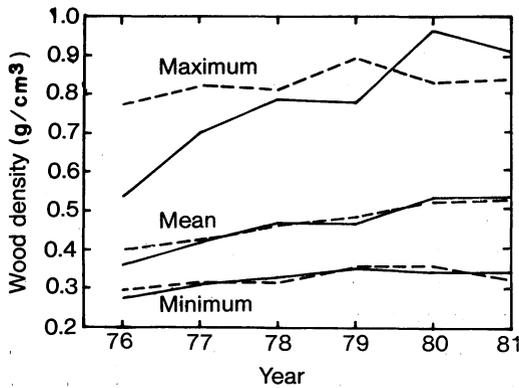
FIG. 3—Density of **P. radiata** from unfertilised (P_0 ———) and fertilised
(P_2 - - - -) trees. Cores were taken at 20% of total tree height and show
minimum, mean, and maximum density from years 6 to 10.

DISCUSSION

The growth of *P. radiata* increased in response to fertiliser up to the rate of 67 kg P/ha (P_2), but there was no additional response to 202 kg P/ha (P_3). The responses in basal area and merchantable volume are of the same order of magnitude as responses to phosphorus fertiliser reported for *P. radiata* grown on phosphorus-deficient sites elsewhere in Australia. For example, in New South Wales volume growth of 14-year-old *P. radiata* was more than doubled after an application of 34 kg P/ha at age 1 (Brockwell & Ludbrook 1962), and an application of 50 kg P/ha at planting doubled the volume of a stand aged 8 years (Waring 1973). In South Australia, fertiliser applications of up to 137 kg P/ha also doubled the volume of *P. radiata* aged 11 years (Raupach *et al.* 1975).

During the first few years after establishment, *P. radiata* has been found to respond to nitrogen in addition to phosphorus on some sites in Australia (Waring 1973, 1981). Rates of nitrogen used in the present experiment were as high as 800 kg N/ha applied over a period of 2.5 years (in combination with 200 kg P/ha), but no response was observed above that to phosphorus alone. When the trees were 2 years old the concentration of nitrogen in the current foliage of trees in control plots was 2.05%. While the nitrogen concentration in the treated plots was significantly lower than this, the mean value of 1.84% was still well above the level required for good growth (Raupach 1967). The mean concentration of nitrogen in the current foliage at 10 years of age was still 1.72%, with little difference between fertiliser treatments. The response of *P. radiata* to phosphorus and nitrogen, alone or in combination, during the establishment phase is thus determined by which element is most limiting to growth on each site.

Data were reported from the experiment when the trees were 2.5 years of age (Cromer *et al.* 1977) and a prediction of volume growth at age 10 was made on the basis of results from an older experiment nearby. Comparison of the observed values with the predicted values showed the variance accounted for was 0.68, with the observed values some 30% lower than those predicted previously. The error was greatest in plots with initially high levels of phosphorus in the foliage, as these did not respond as much as predicted from the earlier experiment which was on a different soil type. A sensitivity analysis in the previous paper indicated that an error in the magnitude of the response did not influence the outcome of the economic analysis (Cromer *et al.* 1977).

The term "spindle stand" has frequently been applied to *P. radiata* plantations suffering from phosphorus deficiency, as diameter growth is reduced more than height. Snowdon *et al.* (1981) observed that average taper (diameter/height) decreased with increasing tree size but, for a given diameter, establishment practices such as weed control and fertiliser application increased average taper and the data presented here are in agreement with their findings.

Total above-ground biomass at 10 years of age was almost doubled as a result of an application of phosphorus fertiliser soon after planting, but there was little change in the fraction of standing biomass observed in the above-ground components of fertilised and unfertilised trees. As tree size increases with age, the proportion of above-ground biomass observed in stem wood increases and the proportion observed in

needles decreases (Forrest & Ovington 1970; Madgwick *et al.* 1977). It might be expected that an increase in tree size as a result of fertiliser application would have a similar effect, but this was not observed in the present study or the one reported by Flinn *et al.* (1982).

The ratio of needle biomass to total above-ground biomass observed in several studies was found to be inversely related to tree height (Fig. 4). The proportion of needle biomass relative to the total above-ground biomass thus may not change as a result of fertiliser application unless there is a response in height growth. A reduction in the proportion of needle biomass with increasing tree age may well be due primarily to the increase in height with age. The lack of any marked change in the proportion of needles and other components (present study, and Flinn *et al.* 1982) thus probably relates to the lack of a response in height. Temporary changes in foliar biomass can occur because of sudden changes in fertility or water availability (Cromer *et al.* 1984) and short-term changes in proportions could be expected.
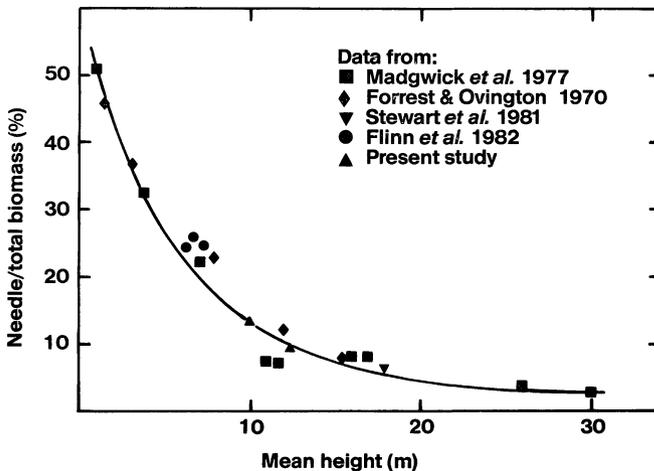
FIG. 4—Relationship between stand mean height and live needle biomass/total biomass. Data from several studies in Australia and New Zealand.

A method which would enable stand biomass to be estimated from simple measurements of tree height and diameter would be a valuable aid to the forest manager. The rate of stem growth in *P. radiata* is constant when expressed as the increase in total volume of wood per unit of basal area for unit increase in height (Cromer 1961; Beekhuis 1966). This observation enabled stand volume to be estimated without a knowledge of site quality or previous thinning history. When applied to biomass data reported in the literature, the method was found to be equally applicable to stem wood biomass. Data from Madgwick *et al.* (1977), Forrest & Ovington (1970), Stewart *et al.* (1981), and the present study were recalculated in terms of stem wood biomass of the stand per unit of basal area and plotted against height (Fig. 5). A correlation coefficient of 0.96 resulted using the combined data from Australia and New Zealand. The method is similar to that used by Madgwick *et al.* (1977) in which a direct relationship was found between stem biomass and basal area times height.

Stemwood biomass = (0.24 + 0.14H) BA
$r^2 = 0.96$
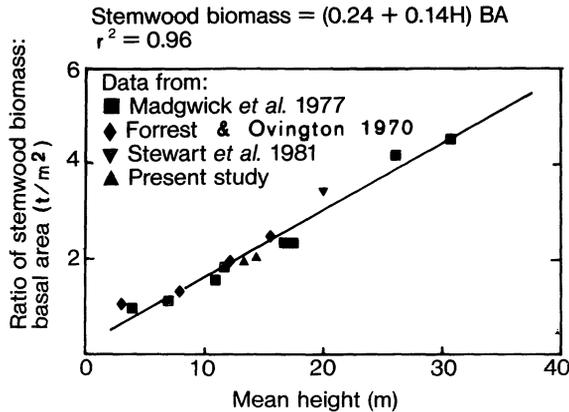
FIG. 5—Relationship between stem wood biomass (per unit of basal area) and stand mean height. Data from several studies in Australia and New Zealand.

Although several studies have shown a decrease in wood density as a result of fertiliser application (McKinnell 1970; Nelson *et al.* 1980; Cown & McConchie 1981), most authors have concluded that the effects of fertiliser treatment on wood density were minor and of little technological significance. Bamber & Burley (1983) reviewed the literature on wood properties in *P. radiata* and noted that the wood of fertilised forests ought not to be substantially different from the wood of unfertilised but vigorous forests. They also suggested that whilst acceleration of growth associated with heavy thinning or fertiliser application can reduce wood density, the effect of growth rate *per se* does not significantly influence density where regular growth rates are maintained.

Samples taken at 4 years of age from the experiment reported here were found to have wood densities of 0.41 g/cm³ in the unfertilised plots compared with 0.34 g/cm³ in P₂ plots (Nelson *et al.* 1980). The present study, however, shows that there was no significant difference between unfertilised and fertilised plots and that the early differences had little effect on mean density at 10 years. This conclusion is also applicable to the effect of fertiliser on minimum and maximum density.

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