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Within-tree, between-tree, and geospatial variation in estimated *Pinus radiata* bark volume and weight in New Zealand

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Abstract

Background: Many studies have been carried out to quantify the wood properties of radiata pine, but few have explicitly looked at quantifying radiata pine bark. Bark is of increasing interest for many reasons, e.g. energy source, potential source of bioproducts, log handling methods and costs, and phytosanitary methods.

Methods: Over-bark and under-bark diameter measurements recorded from over 1000 discs taken from fixed heights in 150 trees were used to estimate bark volume percentages. The mature trees were from a single seed source and had been planted at 17 sites throughout New Zealand. Bark volume percentages were converted to bark weight percentages using data from 390 trees from the central North Island of New Zealand.

Results and conclusions: This study confirmed earlier research that bark accounts for 12 to 13 % of over-bark volume and 7 to 8 % of over-bark green weight for mature radiata pine boles prior to felling and log handling. It also showed that bark volume percent varied with location in a stem, tree size, and site (mean annual temperature).

Keywords: Green bark density; Temperature; Conversion factors; Over-bark volume percent

Background

The term bark refers to all tissues of a woody stem or root occurring just outside of the vascular cambium, i.e. all tissues that could be stripped away from the woody core. Bark formation is initiated by the process of cell division at the living cambium, which separates the woody stem (xylem on the inside) from the phloem, the food-conducting tissue on the exterior side. Bark is critical to tree survival, serving two very important functions. The outer, mostly dead tissues (outer bark), form a protective barrier between the plant axis and the abiotic (wind, rain, fire, frost, and physical damage) and biotic (insects, fungi, herbivores) environment. Once the tree is felled, however, bark has minimal value and may represent a net financial loss to the forest industry (Marshall et al. 2006). However, increasingly, biomass of traditionally non-commercial components such as broken tops, dead trees, bark, needles, and branches is becoming important for carbon accounting, landscaping products, animal bedding, and substitutes for fossil fuels (Hall 2000; Temesgen et al. 2015). For these purposes, more qualitative and quantitative data are required.

The presence of bark on stems presents a challenge for foresters wishing to estimate the volume of wood contained in stems (Li and Weiskittel 2011), and systems have been developed for predicting stem volume based on bark thickness (BT) measurements at breast height (Gordon 1983; Laasasenaho et al. 2005).

Stem diameter is one of the most obvious commercial indicators in forestry. Bark thickness on a tree varies not only by species (Miles and Smith 2009) but also by the rate of growth, the genetic constitution of each tree, position along the bole (Laasasenaho et al. 2005), and geographic location (Antony et al. 2015). Thus, one BT function with the same set of parameter values cannot be applied to all trees, even for the same species. When under-bark measurements are not available, various approaches have been proposed to estimate and predict diameter under bark (DUB) at a certain stem height. Numerous taper equations (Cao and Pepper 1986; Gordon 1983; Kitikidou et al. 2014) have been published and are commonly used to predict DUB at

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any given height along the tree bole. The functions commonly incorporate factors such tree age, height in stem, and breast height diameter (DBH).

Miles and Smith (2009) compiled information on the properties of wood and bark for 156 species in the USA for the estimation of biomass. Bark in 24 pine species varied from 8.9 % (*Pinus contorta* Douglas) to 20.4 % (*Pinus jeffreyi* Balf.) with radiata pine (*Pinus radiata* D.Don) reported to have 11.8 % of over-bark volume.

The density and moisture content (MC) of bark and its percentage weight relative to wood are important criteria for biomass calculations and for log handling and transport cost determination. Antony et al. (2015) set out to identify geographical variation in loblolly pine (*Pinus taeda* L.) bark and wood quality and to quantify the responses following silvicultural practices that included planting density, weed control, and fertiliser application. Trees were destructively sampled across the southern USA. Bark and wood properties were measured from discs collected at multiple heights from sampled trees and used to compute the whole-tree bark and wood properties. Significant regional variation was observed for both bark and wood properties. Bark thickness and bark percentage decreased with stem height and were positively correlated with proximity to the ocean (possibly related to temperature), tree age, and DBH. Bark and wood basic density showed an increasing trend from inland to coastal regions and vice versa for bark and wood MC. Effects of silvicultural treatments on the other hand were generally minimal.

Utilisation of bark in New Zealand has been of interest for over 40 years (Harris and Nash 1973). Products currently derived from radiata pine bark include hog fuel, compost, and landscaping products, but potentially, a wider range of options is possible (Ferreira et al. 2015). Bark is comprised of about 65 % extractable chemicals with the remaining insoluble material having a similar composition to that of wood. The extractable chemicals include terpenes, waxes, resin acids, phenols, and polyflavonoids (mainly comprised of tannins). The chemicals that have shown the greatest opportunity for commercial exploitation are the polyflavonoids (Uprichard 1986). The two main areas of interest are in the use of tannins as adhesives and in the antioxidant potential of the lower molecular weight flavonoids (Jorge et al. 2002; Li et al. 2015).

On the assumption that the annual harvest in New Zealand will be around 30 million m^3 by 2020 (MAF 2010), and the proportion of bark around 10–12 % (Webber and Madgwick 1983), up to 3 million m^3 per year of bark could potentially be associated with felled stems. Depending on tree age, season, and the type of harvesting machinery, significant proportions of this will unavoidably end up on the forest floor, at landing sites, at processing plants, and at marine ports. The amount of bark reaching a processing plant or port can vary from 5 % of over-bark volume in spring to 10 % in autumn (Cown 1999).

Radiata pine plantations are intensively managed and generally harvested between 25 and 30 years of age. While numerous wood-quality studies have been carried out, relatively few of them report on bark characteristics because the main focus has been on the wood characteristics of the stem and commercial logs.

Despite its significance, only limited information is available about radiata pine bark properties and bark proportion variation. The quantity and quality of bark produced from plantation-grown radiata pine is important, especially as material to be disposed of or used as an alternative fuel source or bioproduct. Nevertheless, statistics on the quantity of bark produced and used are not widely available. Part of the reason for the paucity of statistics is probably that bark usually has been considered a waste to be disposed of at the lowest possible cost. Data on physical characteristics are important factors related to biomass production and with handling costs of the felled stems through the forest to wood processor supply chain.

Radiata pine wood-quality studies (mostly unpublished) have most commonly involved measuring both diameter over bark (DOB) and DUB, but a few have been specifically aimed at removing bark samples for determining the physical properties of bark independent of the wood. Some of the main results have been the following:

- Standing radiata pine trees had an average of 10 to 18 % bark volume (depending on the assessment method). Bark data were very variable between stems within crops.
- BT was highly influenced by stem age and stem height, although the difference between BT on young and older trees of the same diameter was only of the order of 2–3 mm.
- Bark MCs (based on volume and weight measurements on excised small samples) were strongly affected negatively with tree age and positively with height in stem. In young stems, MC was around 100 % (dry weight basis) at the base of the tree, increasing to around 200 % at the top. Equivalent figures for mature stems were 50 and 100 %.
- The bark basic density (based on volume and weight measurements on excised small samples) varied from 300 kg m^{-3} in thinnings (12–14 years) to around 400 kg m^{-3} in 30-year-old stems.
- Bark properties did not appear to be strongly influenced by geographic location or stem diameter within crops.

In the course of a survey of wood properties in the central North Island region of New Zealand (Cown et al. 1984), extensive measurements were taken from discs of 584 trees of ages between 10 and 50 years to assess stem diameters, wood density, and MC by log position. In the process, bark data were also collected in order to better understand the log weight-to-volume relationship (a common basis for log sale whereby log weight is converted to wood volume under bark (Ellis 1993)). It was concluded that bark volume (based on DOB and DUB data) increased with tree age at all sites and decreased with height in the stem. However, some of the more detailed bark data (e.g. green bark density) was not presented in the published report.

This paper utilises previously unpublished data to quantify the variation in radiata pine bark volume from stems grown at sites ranging from the top of the North Island to the bottom of the South Island of New Zealand. It also uses previously unpublished data to convert percentage volume estimates to percentage green weight estimates.

Methods

Data sources

In the first half of the first decade of the millennium, the New Zealand forest industry funded research to characterise wood quality of the radiata pine resource. Trees from a 1978 genetics gain trial established across 17 sites, stretching from the top of the North Island to the bottom of the South Island of New Zealand, were selected for the wood-quality project (Table 1). The trials were established with known genotypes (three open-pollinated commercial seedlots), sited on former state-owned production forests at 22 sites selected to encompass a broad range of climates. Bark thickness was one of the many attributes measured from 1063 discs obtained from the sample trees. Other attributes included radial trends in green and dry wood density, spiral grain, microfibril angle, heartwood, internal checking, resin, stiffness, and stability. Over time, some variation in silviculture has occurred as a result of changes in forest ownership. Several trials were abandoned due to damage from excessive grazing or severe storms. One seedlot (WN/72/2), produced from the Gwavas seed orchard and based on open-pollinated seed from 25 clones of the 850 series selected from the central North Island, was chosen as the fixed genotype for the wood-quality project. It represented some degree of genetic improvement (GF14) (FRI 1987) and was present in sufficient numbers for sampling at 17 of the sites.

A total of 450 trees were sampled for DBH and outerwood density (increment cores), and a selection was made for a much more intensive study of wood properties. A third of the trees were selected to cover the wood density and diameter range at each site and were felled in 2003/2004 and at ages 25 or 26 years. Diameter over bark and DUB were measured at the butt, 1.4 m, 5 m, and then every 5 m up the stem to an approximate top end diameter of 100 mm. Twenty-five of the 1063 sets of measurements were on discs that had been collected at intermediate heights between the standard 5-m intervals, 17.5 m being the lowest and 38 m being the highest. BT varied from 2 to 50 mm.

Table 1 Location of sites where wood-quality data were collected

Forest	Latitude (° S)	Longitude (° E)	Elevation (m)	No. of trees	Range of diameter breast height (mm)
Aupouri	34.88	173.10	38	10	397–539
Athenree	37.46	145.90	100	10	361–600
Ruatoria	37.73	178.26	140	10	376–670
Kaingaroa	38.45	176.68	560	10	429–614
Kaingaroa	38.54	176.42	220	10	370–642
Mohaka	39.06	176.97	280	10	497–704
Lismore	39.99	175.11	50	6	451–706
Ngaumu	41.05	175.88	250	10	351–615
Rabbit Island	41.26	173.12	7	10	329–575
Golden Downs	41.48	172.89	375	10	404–527
Waimea	41.48	173.07	392	10	335–494
Ashley	43.06	172.47	400	9	439–657
Eyrewell	43.41	172.22	195	10	357–453
Waimate	44.70	170.88	473	10	329–613
Longwood	46.14	167.80	196	6	436–720
Rowallan	46.06	167.66	196	7	430–555
Blackmount	45.74	167.70	350	2	417–429

Expected mean temperature averages from a 30-year-period (temp) for each site were obtained from the New Zealand National Climate Database (NIWA 2005). The nearest weather station was used. Where there were significant differences in elevation between the weather station and the trial site, mean temperature was adjusted by an average atmospheric lapse rate of 0.6 °C per 100 m of elevation change. Mean temperatures ranged between 8.7 °C at the bottom of the South Island and 16.1 °C at the top of the North Island.

Unpublished data associated with a regional wood property survey in the central North Island (Cown et al. 1984) were incorporated to present a fuller picture, specifically green wood density based on whole discs (GWD) and green bark density (GBD), derived using the same methods as the aforementioned genetics trials and Antony et al. (2015). These data were used to calculate green density ratios of bark to wood.

Analysis

Bark volume (BVol%), expressed as a percentage of over-bark volume, was calculated using Eq. 1.

$$\mathrm{BVol\%} = 100 * \left(1 - [\mathrm{DUB/DOB}]^2\right) \tag{1}$$

The software packages StatGraphics Plus (Version 5) and Microsoft Excel 2010 were used to develop and test models. Correlation analysis showed that BVol% was related to height (−0.60), DOB (0.45), and mean temperature (0.04) in descending order.

A plot of BVol% against height indicated that BVol% decreased non-linearly with height. Height in regression models was, therefore, transformed using a natural log transformation after first adding one to each height to adequately deal with bark volume measurements at the butt (height = 0).

Plots of BVol% against DOB at fixed heights up the stem (e.g. 0 m, 1.4 m, 5 m, etc.) indicated that BVol% was linearly related to DOB.

BVol% data were checked for outliers. One measurement point was deleted because it went against the trend for all other trees where BVol% decreased from the butt to 1.4 m. It also had the largest BVol% and produced a large residual if it was included in any regression models.

Data were randomly split into two sets. Approximately 80 % of the data were used for model construction and approximately 20 % for model validation.

StatGraphics GLM procedures were used to develop regression models. Initial independent variables selected were transformed height, DOB, and mean temperature. Additional independent variables were the interaction of mean temperature and DOB and the interaction of mean temperature with transformed height. Models were compared based on adjusted R^2 and mean absolute error (MAE) values for the constructed models and average residual and MAE values from the validation data set. Residual plots for the validation data set were visually examined to determine if the residuals were heteroscedastic and normally distributed.

The final model selected was of the form

$$\begin{aligned}\mathrm{BVol\%} = {} & a + b^*\mathrm{Ln}(\mathrm{Ht}+1) + c^*\mathrm{DOB} \\ & + d^*(\mathrm{Ln}(\mathrm{Ht}+1) * \mathrm{temp})\end{aligned} \tag{2}$$

The effect of the three sources of variation on BVol% was demonstrated as follows:

- *Within-tree variation*. BVol% was calculated and plotted for various heights for the median tree from all sites, based on DOB at 1.4 m, assuming the overall mean temperature from all sites.
- *Between-tree variation*. Merchantable tree bark volume percent (MTBVol%) was calculated and plotted for three representative trees (the smallest, median, and largest trees from the total data set) for each of the 17 sites. BVol% was assumed to decrease linearly between measurement points.
- *Geospatial variation*. The same calculations used to demonstrate between-tree variation in bark volume were used to demonstrate geospatial variation.

The ratio of GBD to GWD was calculated for up to six 5.5-m log height classes (0–5.5, >5.5–11.0, >11.0–16.5, >16.5–22.0, >22.0–27.5, and >27.5–33.0) and overall for 21- to 30-year-old trees. Since there was no consistent trend in the ratio between low, medium, and high wood density sites within the data collection region, an assumption was made that the ratios would be applicable to stems located at all 17 sites. The parameter MTBVol% can be converted to bark weight percentage (MTBWt%) using Eq. 3. The same approach was used for converting BVol% to bark weight percentage for individual log height classes up a stem.

$$\mathrm{MTBWt\%} = (\mathrm{GBD/GWD}) * \mathrm{MTBVol\%} \tag{3}$$

Results

The bark volume model

The average bark volume (BVol%) for all sites was 12.6 %. It ranged from 3.4 to 31.3 % for individual discs.

The analysis of variance and summary regression statistics are shown in Table 2 for the final model. The accuracy of the model was highly significant and accounted for 69 % of the variability in bark volume. The MAE for the model was 2.436.

The coefficients for the final model are provided in Table 3. When the model coefficients were applied to the validation data set, the model was unbiased (mean residual = −0.01), the residuals appeared to be homoscedastic and normally distributed, and the MAE was 2.669.

Sources of variation in bark volume

Bark volume decreased exponentially with height in each tree. This trend is illustrated in Fig. 1 and was calculated for the median tree assumed to have grown at the mean temperature from the 17 sites, i.e. 12.4 ° C. In this case, BVol% decreased rapidly from more than 20 % at ground level to 10 % at a 10-m height. It then levelled off to about 8 % for the remaining portion of the stem.

Within a site, MTBVol% was greater for small trees than it was for large trees. This trend is shown in Fig. 2 as calculated for the smallest, median, and largest trees from the combined 17 sites assumed to have grown at all 17 sites. MTBVol% would be expected to be over 7 % greater for the smallest tree than for the largest tree at all sites.

Among sites, there was a 2.1 % difference in calculated MTBVol% for the median tree from all sites with the bark volume being greatest in the warmest climate site (Aupouri) and least in the coldest climate site (Blackmount) (Fig. 2). Assuming that for the same silviculture and rotation age, the median tree for an individual site is likely to be larger for warmer sites than colder sites, then it could be expected that the actual difference between the warmest and coldest sites would be larger than shown.

Conversion to bark weight

The ratio of GBD to GWD for various log height classes is shown in Fig. 3. The increase in this ratio with height is due to three main factors—less fissuring of bark at higher levels, an increase in the actual green density of thinner bark, and an increase in heartwood percentage with height. A whole-tree GBD/GWD ratio of 0.562 was calculated.

For central North Island sites, where the GBD/GWD ratio data were collected, the calculated MTBWt% was 6.8 % for the median tree from the 17 sites. The calculated MTBWt% for the median tree ranged from 6.2 to 7.5 %, being highest for the warmest site.

Table 2 ANOVA and summary statistics for the final regression model

	df	SS	MS	*F*	Significance of *F*
Regression	3	18282	6094.13	616.88	<0.001
Residual	846	8357	9.88		
Total	849	26640			
Adjusted R^2	0.685				
Standard error	3.143				
Observations	850				

Table 3 Coefficients for the final regression model for estimating bark volume (BVol%)

Coefficients	Value	Standard error	*t* stat	*P* value
a	31.2735	0.7850	39.84	<0.001
b	−7.3587	0.3497	−21.04	<0.001
c	−0.0193	0.0013	−14.44	<0.001
d	0.1429	0.0253	5.65	<0.001

Discussion and conclusions

Some wood properties of radiata pine in New Zealand are very well documented, particularly wood density (Cown 1999; Palmer et al. 2013). Information on bark is much sparser.

The data on radiata pine bark volume reported here are in strong agreement with other radiata studies. The bark for the median tree was estimated to be 12.6 % of over-bark volume, similar to earlier estimates of 12 % (Young et al. 1991) and 13 % (Cown et al. 1984) for 50 and 390 mature central North Island radiata pine trees, respectively. It is also similar to the 11.8 % value reported for radiata pine in the USA (Miles and Smith 2009). The amount of bark on a tree was dependent, however, on tree size with the smallest tree estimated to have 7 % more bark than the largest tree, 16.7 and 9.4 % of over-bark volume, respectively.

There was an exponential decrease in bark thickness and volume from the butt upwards in the stem (thickness from about 35 to 5 mm above 30 m; volume from 22 to 8 %). As with the comprehensive southern pine study (Antony et al. 2015), a small decrease in bark volume with mean average temperature was also noted, equivalent to about one quarter of a percent of over-bark volume per degree decrease in mean average temperature.

The data on radiata pine bark weight reported here are also in agreement with other radiata studies. The bark for the median tree was estimated to be 6.8 % of

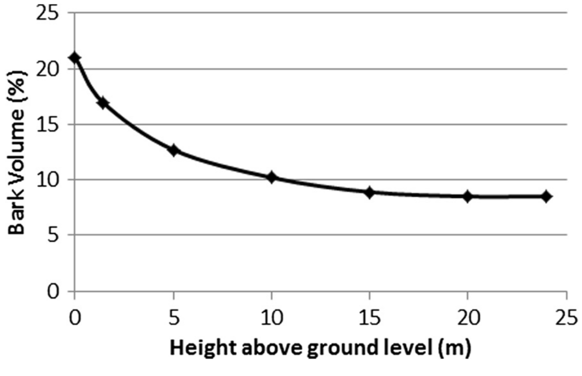

Fig. 1 Variation of calculated radiata pine bark volume (BVol%) with height in the stem for the median tree from all sites

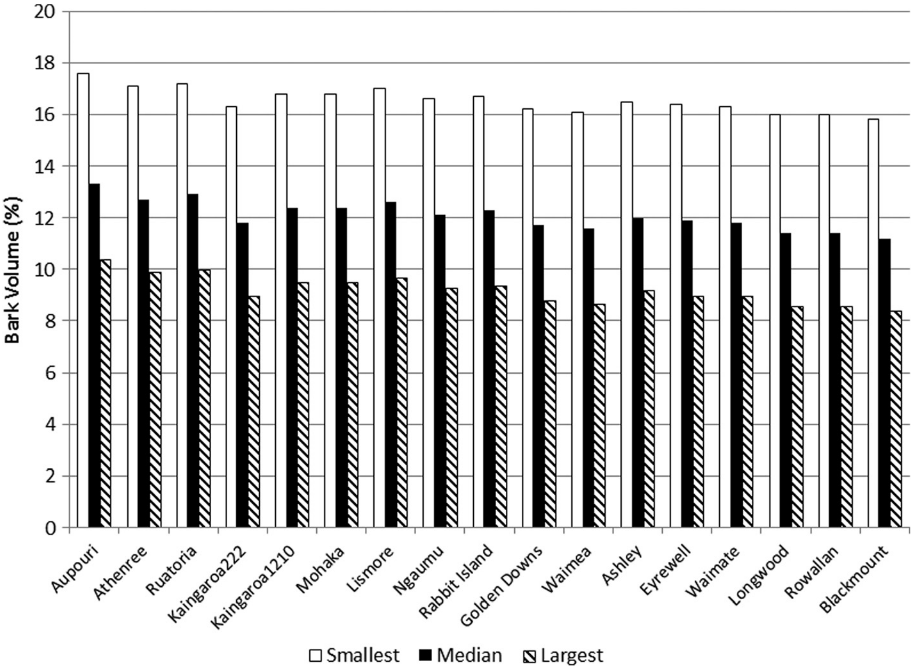

Fig. 2 Variation of calculated merchantable tree bark volume (MTBVol%) with tree size and geospatial location

over-bark weight. This is slightly lower than earlier estimates which ranged from 7 % (Young et al. 1991) to 8.2 % (Cown et al. 1984) on a green weight basis and 8.7 % (Webber and Madgwick 1983) on a dry weight basis for mature central North Island radiata pine tree boles.

The bark weight percentage estimates in this study were dependent on the GBD/GWD ratios. The ratios are likely to be dependent on tree age and tree size. They may also be dependent on season (Gibbs 1958). Chan et al. (2012) found that season exerted no practical effect on whole segment green density for radiata pine. However, it is possible that bark and wood changed differentially in opposite directions as reported by Gibbs (1958) for poplar and willow. Contrary to the work of Chan et al. (2012), Ellis (1993) noted that there is a 4 % difference in weight-volume conversion factors for logs between summer and winter—some of this difference may be due to bark loss during handling.

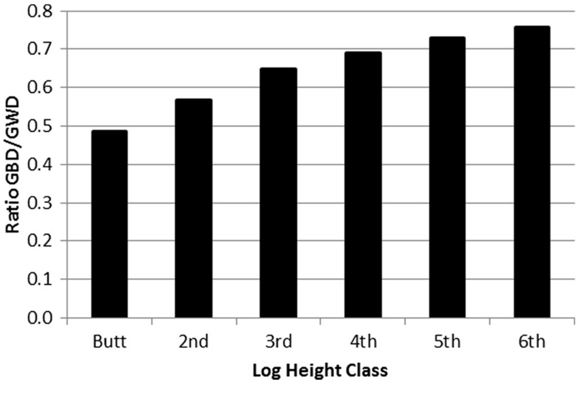

Fig. 3 Variation in the ratio of green bark density (GBD) to green wood density (GWD) with height in the stem for 25- to 26-year-old radiata pine trees from central North Island sites. Log height classes are in increments of 5.5 m: 0–5.5, >5.5–11.0, >11.0–16.5, >16.5–22.0, >22.0–27.5, and >27.5–33.0

It must be noted that the study discs were carefully handled to retain bark, so the results are most relevant to standing trees in the forest. Logs reaching processing sites will inevitably loose a proportion of the bark depending on season and handling systems (Marshall et al. 2006).

This study has confirmed earlier research that bark accounts for 12 to 13 % of over-bark volume and 7 to 8 % of over-bark green weight for mature radiata pine boles. It also shows that bark volume percentage varies with location in a stem, tree size, and site (mean annual temperature). Further work, however, is required to quantify the effects on bark volume percent of tree age and possibly other seed sources. Additionally, further work is required to quantify the effects on green bark to green wood density ratios of tree age, tree size, season, and sites (outside the central North Island) to facilitate the conversion of bark volume percent estimates to bark weight percent estimates.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

GM was the lead author, carried out the data analyses, and drafted the main manuscript. DC contributed to the collection of the data and the preparation of the manuscript. All authors read and approved the final manuscript.

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Plant licences

The local, national, or international guidelines and legislation relating to plants and the required or appropriate permissions and/or licences for the study have been obtained.

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