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PRECISION, EFFICIENCY AND COST OF SHAPES OF FIXED AREA PLOTS FOR PLANTATION AGES OF *Pinus taeda* L. IN SANTA CATARINA STATE

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ABSTRACT - Generally, the forest populations are extensive and frequently require to be inventoried in short term, where the implementation of forest inventory is closely linked to the sampling theory. With objective to compare three different shapes of fixed area plots to estimate parameters of the forest as average diameter, basal area, the number of trees and volume per hectare, evaluating the respective precision, relative efficiency, cost and measurement time in four different ages. The rectangular plot had presented better precision to estimate the average DBH, number of trees and basal area and the circular plot with better precision for volume per hectare. About efficiency, the square plot had presented the best efficiency for the variable average DBH, basal area and volume and the circular plot was the most efficient for the numbers of trees ha^{-1}. The square plot also had shown the lower cost and measurement time to estimate the variables evaluated. The rectangular plot had presented the best precision in the estimative of the variables, as well as, the lower sampling error in the most of the cases evaluated in this study, following the circular plot, and the square plot with lower precision. In relation to the efficiency, the square plot had presented the best performance and the rectangular plot the worst performance in all age classes and evaluated variables. The square plots as the best plot shape to estimate the variables average DBH, number of trees, basal area and volume per hectare.
Keywords: forest inventory, square plot, parameter.

PRECISÃO, EFICIÊNCIA E CUSTO PARA FORMAS DE PARCELAS DE ÁREA FIXA EM IDADES DE PLANTIOS DE Pinus taeda *L., EM SANTA CATARINA*

RESUMO - As populações florestais são geralmente extensas e com frequência necessitam ser inventariada em curto espaço de tempo, onde a realização dos inventários florestais está intimamente vinculada à teoria da amostragem. Diante do exposto, objetivou-se com o presente trabalho comparar três diferentes formas de parcela de área fixa na estimativa de parâmetros da população como diâmetro médio, área basal, número de árvores e volume, avaliando a sua respectiva precisão, eficiência relativa, custo e tempo de medição em três classes de idade. A parcela retangular apresentou maior precisão nas estimativas do DAP médio, número de árvores e área basal e a parcela circular a melhor precisão para o volume por hectare. Na eficiência, a parcela quadrada apresentou maior eficiência para o DAP médio, área basal e volume e a parcela circular a mais eficiente para o número de árvores ha^{-1}. A parcela quadrada também foi a forma que se mostrou como a de menor custo e tempo de medição para as estimativas das variáveis avaliadas. A parcela retangular apresenta maior precisão nas estimativas das variáveis, ou seja, o menor erro de amostragem na maioria dos casos avaliados nesse trabalho, seguida pela parcela circular, sendo a parcela quadrada a de menor precisão. Na eficiência, a parcela quadrada apresenta melhor desempenho e a retangular o pior desempenho em praticamente todas as idades e variáveis avaliadas. Recomenda-se a parcela quadrada como a melhor forma de parcela para a estimativa das variáveis do DAP médio, número de árvores, área basal e volume por hectare.
Palavras-chave: inventário florestal, parcela quadrada, parâmetros.

INTRODUCTION

The forest plantations are the main source in the productive chain of Brazil's forestry, where pine has been advancing in the last decades. According to IBÁ (2019), in national ambit, pine represents 20.43% of forest plantations in the country, whereas in Santa Catarina State, second Acr (2016) this advance is more expressive, representing 82% of the planted forest in the State. For Scolforo and Mello (2006) in obtaining quantitative and qualitative information from forest stand, generally, methodologies of sampling are applied, where pre-defined variables are measured in part of the population and estimate their parameters to the overall plantation.

The success of the forest inventory is relate the correct definition of the size and shapes of the sample units, part of the basic requirements for obtaining accurate information (UBIALLI et al., 2009).

Obtaining this information generate costs which increase with the level of details, required precision, the efficiency of how the variables are undertaken (DRUSZCZ

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et al., 2012). Generally, the forest populations are extensive, with difficult access, and frequently require to be inventoried in short term, the implementation of forest inventory is closely linked to the sampling theory.

For these characteristics, the forest inventories can be compounded in different plot shapes and sizes, where the more used are square, rectangular, strips and circular (OLIVEIRA et al., 2014). Because of that, the majority of the forest inventories executed in the world is based on statistic procedures of sampling, and the of measurement can be controlled by necessary time to install the plot (PÉLLICO NETTO and BRENA, 1997). Also, for these authors, the variation of plot shapes and sizes consist of the fundamental variables to evaluate their practical application, what justifies this proposed research.

Therefore, the objective of this study was compare three different shapes of fixed area plots to estimate parameters of the forest as average diameter, basal area, the number of trees and volume per hectare, corroborating with the respective precision, relative efficiency, cost and measurement time in four different age classes.

MATERIAL AND METHODS

The study was established in plantations of *Pinus taeda* in a forest company located at Northeastern of Santa Catarina State, based on the permanent inventory plots. The sampling process used was random simple, in 80 permanent plots random allocated. With 20 plots for each age class (5, 9, 13 e 17 years old) determined in the forest. These plots were established with fixed area, in shapes circular and square (400 m^2) and rectangular (900 m^2).

The initial spacing used in the planting was 2.5 x 2.5 m, resulting in a density of 1,600 tress per hectare (age 5), and the initial spacing 2.5 x 2.0 m (resulting in a density of 2,000 trees per hectare for age 9, 13 and 17). A rotation of 17 years has been implemented, with this age standardized to younger plantations. With the target of 600 trees per hectare at the end of the rotation and only commercial thinning to be applied at 10 and 14 years of age for all plantations.

For comparing different ages and plot types, had been considered some statistical parameters for the evaluation, as well as, standard deviation, stand error, the coefficient of variation, and the relative sampling error. The ANOVA was calculated to determinate the plot shapes difference for each age and variable, on a significance level of 5%, and where there is the significant difference, it had been applied the Tukey test. The precision was evaluated by calculating the relative sample error to verify the most precise methodology (Equation 1).

$$Er = \pm 100 * \frac{t.S_x}{x} \qquad \text{Equation 1}$$

Where:
Er = relative sample error,
t = student table,
S_x = standard error of the estimative and
x = average

The relative efficiency (RE) was calculated to the plot's size and shape presenting higher value to determine the more efficient (MIRANDA et al., 2015a). For this calculation was considered the coefficient of variation for the different plot sizes and shapes. To calculate the relative efficiency was not considered the shift time between plots, which was only applied to the cost calculation (Equation 2).

$$RE = \frac{1}{T_i . CV^2} \qquad \text{Equation 2}$$

Where:
RE = relative efficiency,
T_i = time to measure the plot "i" and
CV = coefficient of variation of the plot "i"

The estimative of average time of measurement was undertaken by the sum of time to measure each plot, then, divided by the number of plots measured.

RESULTS AND DISCUSSION

Precision Analysis

The statistical analysis result for the variables average diameter at 1.3 m height (DBH), the average number of trees per hectare, basal area and average volume per hectare, for the three different plot shapes evaluated in 4 age classes of the forest population is demonstrated in the Table below.

In the estimative of the average DBH, the rectangular plot showed more precise for the ages of 5, 13 and 17 years old. For the age of 9 years old, the square plot showed more precise (Table 1). However, for all age classes and plot shapes had presented sampling error close or inferior to 10% for the estimative of the average DBH. Which is written in the literature as the maximum value accepted for sampling error in inventory for planted forests to estimate the interested variable (SANQUETTA et al., 2014; PÉLLICO NETTO and BRENA, 1997; CAIN and CASTRO, 1959).

The absolute value found for average DBH were closed between all age classes, varying in less than one unit (cm) for all plot shapes, demonstrating that the plot shapes estimate with satisfactory precision. In addition, it was identified increasing in the average DBH precision for younger forest population compared to older forest populations, because the increase in standard deviation at older ages was less than the average diameter.

TABLE 1 - Statistical Analysis for the variable average DBH for three different plot shapes in four age classes studied.

	Plot Shapes		
Variables	Rectangular	Circular	Square
	5 years old		
Average DBH (cm)	16.70	16.74	16.79
Standard Deviation (cm)	1.03	1.15	1.10
Standard Error (cm)	0.23	0.26	0.25
Coeficient of Variation (%)	6.19	6.88	6.54
Relative Sampling Error (%)	10.71	11.89	11.31
	9 years old		
Average DBH (cm)	20.89	20.94	20.97
Standard Deviation (cm)	1.32	1.24	1.21
Standard Error (cm)	0.29	0.28	0.27
Coeficient of Variation (%)	7.90	5.92	5.78
Relative Sampling Error (%)	10.92	10.24	10.00
	13 years old		
Average DBH (cm)	22.62	22.64	22.59
Standard Deviation (cm)	1.34	1.45	1.52
Standard Error (cm)	0.30	0.32	0.34
Coeficient of Variation (%)	8.02	6.40	6.71
Relative Sampling Error (%)	10.24	11.07	11.61
	17 years old		
Average DBH (cm)	28.47	28.52	28.55
Standard Deviation (cm)	1.44	1.62	1.63
Standard Error (cm)	0.32	0.36	0.37
Coeficient of Variation (%)	8.62	5.66	5.72
Relative Sampling Error (%)	8.75	9.79	9.90

In the estimative of the number of trees, the rectangular plot presented the best results for the three age classes of the plantation (5, 9 and 17 years old) and the circular plot presented the best precision for the age 13. The square plots had not presented the best precision for any age class in the estimative of this variable. The lower sample error for this variable was found in the younger plantations in relation to the older plantations, because the commercial thinning caused greater dispersion in the tree number between the plots, generating a lower precision (Table 2).

The average number of trees per hectare presented a lower estimative when applied in square plots (17.91%) and circular plots (18.09%) in relation to rectangular plots for the age of 13, it being the only age where the rectangular plot had not achieved the best performance. For this age, it all forms of parcels show the sampling error superior of 28%, where this precision was not acceptable for the number of trees per hectare, this can be explained by the fact that commercial thinning has been performed at 10 years of age, which may have caused the largest dispersion for that variable.

In the estimative of the basal area, as similar to the estimative of the number of trees per hectare, the square plots had not presented the best precision in any age class. However, it was the shape type with second best precision in most of the age classes, except the age 17. In the estimative of this variable, the age 5 and 17 the rectangular plot had presented the best precision, and for the age 9 and 13 the circular plot had presented best precision (Table 3).

Druszcz et al. (2010) in a plantation of *Pinus taeda* in the region of Campos Gerais in Paraná State, also evaluated the circular plot for the estimative of same variables showed in this study. However, for overall sampling were found a sample error inferior, as an example, for the estimative of the basal area, the error was ±3.61% against ±16.10% for this study, for 9 years old. For all age classes evaluated in this study, all shape types presented high sample error, what had presented above 15% of relative sampling error, obtaining 32.51% for rectangular plots in the plantation at age 13, can be explained by the recent occurrence of Commercial thinning at age 10.

TABLE 2 - Statistical Analysis for the number of trees for three different plot shapes in four age classes studied.

	Plot Shapes		
Variables	Rectangular	Circular	Square
	5 years old		
Average number of trees ha^{-1}	1,531	1,455	1,456
Standard Deviation (unit)	78.67	153.81	139.52
Standard Error (unit)	17.59	34.39	31.20
Coeficient of Variation (%)	5.14	10.57	9.58
Relative Sampling Error (%)	8.88	18.28	16.57
	9 years old		
Average number of trees ha^{-1}	1,551	1,397	1,397
Standard Deviation (unit)	47.04	129.50	130.26
Standard Error (unit)	10.52	28.96	29.13
Coeficient of Variation (%)	3.07	9.27	9.32
Relative Sampling Error (%)	5.24	16.02	16.12
	13 years old		
Average number of trees ha^{-1}	1,393	1,141	1,143
Standard Deviation (unit)	278.34	189.23	190.37
Standard Error (unit)	62.24	42.31	42.57
Coeficient of Variation (%)	18.17	16.58	16.64
Relative Sampling Error (%)	34.54	28.67	28.78
	17 years old		
Average number of trees ha^{-1}	690	657	657
Standard Deviation (unit)	75.87	104.22	104.22
Standard Error (unit)	16.96	23.30	23.30
Coeficient of Variation (%)	4.95	15.85	15.85
Relative Sampling Error (%)	19.01	27.41	27.41

TABLE 3 - Statistical Analysis for the basal area for three different plot shapes in four age classes studied.

	Plot Shapes		
Variables	Rectangular	Circular	Square
	5 years old		
Basal area (m² ha^{-1})	34.93	33.31	33.47
Standard Deviation (m²)	4.46	5.99	5.36
Standard Error (m²)	1.00	1.34	1.20
Coeficient of Variation (%)	12.77	17.98	16.02
Relative Sampling Error (%)	22.09	31.09	27.70
	9 years old		
Basal area (m² ha^{-1})	55.07	49.48	49.58
Standard Deviation (m²)	7.22	4.91	5.06
Standard Error (m²)	1.61	1.10	1.13
Coeficient of Variation (%)	20.66	9.92	10.21
Relative Sampling Error (%)	22.66	17.15	17.65
	13 years old		
Basal area (m² ha^{-1})	57.40	46.98	46.90
Standard Deviation (m²)	10.86	6.27	6.74
Standard Error (m²)	2.43	1.40	1.51
Coeficient of Variation (%)	31.08	13.35	14.37
Relative Sampling Error (%)	32.71	23.08	24.84
	17 years old		
Basal area (m² ha^{-1})	44.76	42.42	42.49
Standard Deviation (m²)	4.10	4.19	4.09
Standard Error (m²)	0.92	0.94	0.91
Coeficient of Variation (%)	11.74	9.89	9.62
Relative Sampling Error (%)	15.85	17.10	16.63

In the estimative of the volume per hectare, the circular plot showed the best precision at the ages 9 and 13. For the age of 5 years old, the rectangular plots achieve the best result in relation to the precision. The square plots achieved the best result for plantations at the age 17. To emphasize that this variable was registered the higher relative sampling error, hitting values up to 51.63%, when it was observed a decrease in the sampling error for youngest plantations in relation to oldest plantations. However, it was registered high values, above 18%, maintaining the precision above of the maximum required for the sampling error (Table 4).

TABLE 4 - Statistical Analysis for volume for three different plot shapes in four age classes studied.

	Plot Shapes		
Variables	Rectangular	Circular	Square
	5 years old		
Average Volume (m^3 ha^{-1})	110.34	106.89	107.68
Standard Deviation (m³)	27.89	31.91	29.08
Standard Error (m³)	6.24	7.14	6.50
Coeficient of Variation (%)	25.28	29.86	27.01
Relative Sampling Error (%)	43.71	51.63	46.70
	9 years old		
Average Volume (m^3 ha^{-1})	259.59	262.07	263.20
Standard Deviation (m³)	43.99	42.90	43.40
Standard Error (m³)	9.84	9.59	9.70
Coeficient of Variation (%)	39.87	16.37	16.49
Relative Sampling Error (%)	29.30	28.31	28.51
	13 years old		
Average Volume (m^3 ha^{-1})	334.61	320.46	319.56
Standard Deviation (m³)	62.92	51.32	57.44
Standard Error (m³)	14.07	11.47	12.84
Coeficient of Variation (%)	57.03	16.01	17.97
Relative Sampling Error (%)	32.52	27.69	31.08
	17 years old		
Average Volume (m^3 ha^{-1})	378.89	381.09	382.10
Standard Deviation (m³)	40.95	41.54	40.10
Standard Error (m³)	9.16	9.29	8.97
Coeficient of Variation (%)	37.11	10.90	10.50
Relative Sampling Error (%)	18.69	18.85	18.15

In absolute terms, for the estimative of the volume per hectare, the difference between shape types were closed for all age classes (less than 15 m³), which represent difference below 5%. The same result was observed for Almeida et al. (2016), where the proportional difference in the estimative of volume for circular plots and rectangular plots achieve the same performance for *Eucalyptus* plantation.

In plantation of *Tectona grandis*, implemented by Miranda et al. (2015b), evaluated the same three different plot shapes to estimate the average DBH, the number of trees, basal area and volume per hectare, where different of this study, the circular plot presented the best precision for the mentioned variables.

To determinate if had difference between average evaluated in this study, it was applied the variance analysis (ANOVA), on the level of 5% of significance, as it expressed in Table 5, where it was not found significative statistic differences for variables as average DBH and volume per hectare in any age class evaluated. In study implemented by Almeida et al. (2016) comparing the estimative of volume in plantation of *Eucalyptus* with 7 years, also was not identified significative difference between circular and rectangular plots.

TABLE 5 - F-value of Variance Analysis for the measured variables and age class studied.

Variables	Age class				Critic value
	5 years	9 years	13 years	17 years	
Average DBH	0.033	0.021	0.005	0.012	3.159
Nº of Trees	2.346	13.223	8.417	0.769	
Basal Area	0.567	6.032	10.802	2.074	
Volume	0.074	0.036	0.432	0.032	

For the number of trees per hectare and basal area were identified the existing difference between one or more variable averages for plantations with 9 and 13 years old. To verify between which plot shape the difference exist was applied the Tukey Test as the result is expressed in Table 6. According with to result of Tukey test, there were statistical difference for the average of number of trees per hectare and basal area for two age classes evaluated (9 and 13 years old), which in both cases the difference is in the rectangular plot, for the other plot shapes, circular and square, where between themselves, it was not observed significative difference for 5% of significance.

TABLE 6 - Tukey test for the number of trees and basal area in the three plot shapes studied.

Plot Shape	9 years		13 years	
	Number of trees ha^{-1}	Basal area	Number of trees ha^{-1}	Basal area
Rectangular	1,552 a*	573.16 a	1,393 a	590.95 a
Circular	1,398 b	515.07 b	1,141 b	483.53 b
Square	1,398 b	516.61 b	1,144 b	482.43 b

*Means followed by the same lowercase letter in the column do not differ by the de Tukey test at 5% probability error.

Efficiency Analysis

The relative efficiency for the estimative of variables is presented in Table 7, where the plot shape that presented the higher value was the most efficient. In the estimative of average DBH the square plot had presented the best efficiency for three age classes of the plantation (5 years – 2.66, 9 years – 3.27 and 17 years – 6.13), and the circular for the plantation at 13 (3.89). However, the square plot was the second more efficient at this age, but with the value very close (3.79). The rectangular plot had presented the lower efficiency in the estimative of this variable for all age classes, always maintaining below 1.

In plantation of *Pinus* implemented for Druszcz et al. (2010) in Campos Gerais of Paraná State, comparing circular plots with the Bitterlich method, for plantations at age 9, the circular plot had presented best efficiency for the estimative of average DBH (4.51). Opposite this study, where at the same age, the circular plot was the second more efficient (2.99).

The rectangular plot also presented the best relative efficiency when tested to the same variables in natural forest, as confirmed by Sydow et al. (2017), who tested rectangular plots of different sizes in conjunction with square plots, also tested in different sample processes, presenting the same results for both.

For the estimative of the number of trees per hectare, observed opposite performance compared the previous variable. Where the rectangular plot had presented the best efficiency for three age classes of the plantation (5 years – 1.44, 9 years – 4.37 and 17 years – 2.89), and for plantation at 13 the square plot had presented the best efficiency (0.62). The rectangular plot had presented the lower efficiency (only 0.16), because it was the plot shape with the bigger area between the plot shapes evaluated. Consequently, it spent longer measurement time, what affected directly in the decreasing of efficiency. Also at this age, it was the plot shape with higher coefficient of variation. For the efficiency on the estimative of basal area, had observed the same performance that the estimative of average DBH, where the square plot was the most efficient at ages of 5, 9 and 17 years old (0.57, 1.22 and 0.9 respectively).

For plantation of 13 years old the circular plot achieved the best efficiency in the estimative of basal area, in this variable the square plot was the second more efficient, presenting similar results (0.89 for the circular plot, and 0.82 for the square plot). This result also found for a plantation of Tectona grandis, also with 13 years old implemented by Miranda et al. (2015b). For Calvalcanti et al (2009) e Queiroz (1977) the most efficient shapes were square and rectangular, respectively. For the estimative of volume per hectare, the square plot had the best efficiency in three age classes evaluated (5, 9, 17 years old) and the circular plot was more efficient for plantation at age 13, the same performance found in the estimative of Average DBH and basal area. However, it was the variable with worst results of efficiency, where only the plantation at age 17 had an efficiency larger of 0.7, which according to Miranda et al., (2015), this is considered a minimum value for good performance evaluation (the circular plot had an efficiency of 1.55 and the square plot 1.82). This difference in the efficiency for different plot shapes and sizes, second Nakajima et al. (1998) vary according to the forest type, their respective conditions, slope, plantation age and other aspects.

The rectangular plot, for *Tectona grandis* plantation, also had the lower efficiency in the estimative od average DBH, the number of trees per hectare, basal area and volume per hectare, where it was compared with others sampling methods, as Prodan and Bitterlich, in study implemented by Miranda et al. (2015a).

It is important to emphasize that for the volume per hectare the rectangular plot achieve the lower rate of efficiency, where for any age class of the plantation had values larger of 0.06. The cause of this low efficiency can be explained, because in this plot shape the coefficient of variation was the highest found between other variables evaluated, values up to 57.03%. However, the rectangular plot had bigger area for measurement than the others, spending longer measurement time, what directly affect in the decreasing of efficiency.

Analyzing the cost for each plot, was possible to determinate in Table 4 that the square plot had presented the lower cost of measurement, followed by the circular plot. The rectangular plot had presented the higher cost of measurement basically the triple than the square plot, which achieved the best result. This result was expected because the rectangular plot had more than a double of the area, in relation to the plot shapes evaluated (900 m² against 400 m²).

TABLE 7 - Relative efficiency for the estimative of variables in four age classes for three different plot shapes.

Variables		5 years old		
	Plot shape	Rectangular	Circular	Square
	Average time (min)	262.60	91.86	88.02
	Average cost/pot (R$)	26.66	9.32	8.93
DBH (cm)	CV(%)	6.19	6.88	6.54
	ER	0.99	2.30	2.66
Number of trees ha^{-1}	CV(%)	5.14	10.57	9.58
	ER	1.44	0.97	1.24
Basal area (m^2 ha^{-1})	CV(%)	10.40	14.61	14.17
	ER	0.35	0.51	0.57
Volume (m^3 ha^{-1})	CV(%)	25.28	29.86	27.01
	ER	0.06	0.12	0.16
		9 years old		
	Average time (min)	242.40	95.20	91.60
	Average cost/pot (R$)	24.61	9.66	9.30
DBH (cm)	CV(%)	7.90	5.92	5.78
	ER	0.66	2.99	3.27
Number of trees ha^{-1}	CV(%)	3.07	9.27	9.32
	ER	4.37	1.22	1.26
Basal area (m^2 ha^{-1})	CV(%)	14.96	9.31	9.47
	ER	0.18	1.21	1.22
Volume (m^3 ha^{-1})	CV(%)	39.87	16.37	16.49
	ER	0.03	0.39	0.40
		13 years old		
	Average time (min)	185.80	62.60	58.60
	Average cost/pot (R$)	18.86	6.35	5.95
DBH (cm)	CV(%)	8.02	6.40	6.71
	ER	0.84	3.89	3.79
Number of trees ha^{-1}	CV(%)	18.17	16.58	16.64
	ER	0.16	0.58	0.62
Basal area (m^2 ha^{-1})	CV(%)	26.52	13.41	14.40
	ER	0.08	0.89	0.82
Volume (m^3 ha^{-1})	CV%	57.03	16.01	17.97
	ER	0.02	0.62	0.53
		17 years old		
	Average time (min)	131.20	54.40	49.80
	Average cost/pot (R$)	14.33	5.52	5.06
DBH (cm)	CV(%)	8.62	5.66	5.72
	ER	0.95	5.73	6.13
Number of trees ha^{-1}	CV(%)	4.95	15.85	15.85
	ER	2.89	0.73	0.80
Basal area (m^2 ha^{-1})	CV(%)	11.05	14.42	14.97
	ER	0.58	0.88	0.90
Volume (m^3 ha^{-1})	CV(%)	37.11	10.90	10.50
	ER	0.05	1.55	1.82

CONCLUSIONS

The rectangular plot had presented the best precision in the estimative of the variables, as well as, the lower sampling error in the most of the cases evaluated in this study, following the circular plot, and the square plot with lower precision.

In relation to the efficiency, the square plot had presented the best performance and the rectangular plot the worst performance in all age classes and evaluated variables.

After all results had been evaluated, we recommend the square plots as the best plot shape to estimate the variables average DBH, number of trees per hectare, basal area and volume per hectare, because it presented best relative efficiency and lower measurement costs.

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