

Developing the Allometric Equations for Estimating Above-Ground Biomass of *Vachellia tortilis* Using Destructive Sampling in Oman

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How to cite this paper: Al Rahbi, R., & Sulaiman, H., & Wesonga, R. (2025). Developing the Allometric Equations for Estimating Above-Ground Biomass of *Vachellia tortilis* Using Destructive Sampling in Oman. *Open Journal of Forestry*, 15, 23-34. <https://doi.org/10.4236/ojf.2025.151002>

Received: November 8, 2024

Accepted: November 29, 2024

Published: December 2, 2024

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Abstract

Biomass models to estimate carbon stocks in arid environment are very limited. This study employed destructive sampling to develop a new biomass model for *Vachellia tortilis*, a widely known species in the Sultanate of Oman. Twenty trees with a diameter at stump height (DSH) ranging from 18.5 cm to 150 cm were selected based on DSH and height variations for destructive sampling in As Saleel Natural Park Reserve (SNPR) in Al Sharqiyah governorate, South of Oman. Each tree was excavated and cut into three parts: Stems, Branches, twigs, and leaves. The total fresh weight of each tree was obtained in the field using a 300 balance. Sub-samples (250 - 300 grams) were taken from each part of the tree and transferred to the laboratory for dry weight determination. Linear multiple regression analysis was done using SPSS software between the three variables, DSH, H, CA (x) and the total dry biomass (y). Five models were tested for the best-fit model based on R-Square and Mean Square Error (MSE). Model 5 was the best-fit model, including the LOG of DSH and the LOG of CA ($R^2 = 0.97$, $MSE = 0.114$). The models developed in this research fill a critical gap in estimating the AGB of terrestrial native species in Oman and other countries with similar ecological and climate conditions.

Keywords

Protected Area, *Vachellia tortilis*, Best Fit Model, Linear Regression

1. Introduction

Accurate estimation and measurement of carbon sequestration potential are

necessary due to the expanding understanding of the role that trees play in climate change adaptation and mitigation (Bayen et al., 2020). Protected areas (PAs) are extremely important for enhancing the functional role of the trees. Therefore, they must be documented and quantified scientifically in terms of their carbon sink potential. Their potential to sequester carbon is due to the presence of woody plants in the reserve (Ali et al., 2022). They provide many ecosystem services, such as carbon storage (Ouyang et al., 2016). The stock of ecosystem carbon in terrestrial PAs is approximately 20% of all terrestrial ecosystem carbon stocks (Melillo et al., 2015). Any nature conservation action must consider woody vegetation's biomass and carbon sequestration potential (Shiferaw et al., 2022).

To absorb and store atmospheric CO₂, the terrestrial ecosystem is crucial. There are currently five significant carbon sinks known in terrestrial ecosystems. These include soil organic matter, litter, woody debris, below-ground and above-ground biomass (Vashum & Jayakumar, 2012). A healthy habitat that offers ecosystem services, including supplying, provisioning, regulating, esthetic, and cultural services, is one with a high woody-biomass content. Additionally, woody biomass retains significant carbon dioxide since about 50% of tree dry biomass is considered carbon (Malhi et al., 2002). Usually, forest in tropical areas varies according to the climate, topographical condition, and species compositions (Daba & Soromessa, 2019); therefore, topography, climate, and the composition of woody species all have an impact on biomass in the tropics (Pati et al., 2022). However, errors in biomass estimation can be reduced by using an allometric equation specific to the local habitat (Djomo & Chimi, 2017). Using a general equation developed in different zones worldwide can result in an inaccurate estimation of species-specific biomass because there will also be a difference in the geological area, tree size, and growth stages (Henry et al., 2011; Navar et al., 2002). Therefore, developing species-specific allometric biomass equations designed to calculate the biomass of a specific species in a particular biome is crucial for providing more precise estimates (Litton & Kauffman, 2008).

The common variables in allometric equations that, separately or collectively, explain biomass are diameter at breast height (DBH), height, and Crown Area (CA) (Pati et al., 2022). Surveying and creating an allometric equations database are critical for reducing costs and efforts while making it available to researchers, practitioners, and decision-makers (Mahmoud et al., 2016). The most accurate method for estimating biomass is destructive or harvesting methods (Pati et al., 2022).

Based on dendrometry measurements, the research aimed to create site and species-specific allometric functions using the destructive harvesting method to predict AGB for the most dominant woody species, *Vachellia tortilis*. The study objective is to develop a species-specific model for accurate estimation of biomass and C-stocks of *Vachellia tortilis* by researchers and practitioners in Oman which can also be applied to other regions with the same ecological and climatic conditions.

2. Material & Methods

2.1. Study Area

Al Saleel Nature Park Reserve (SNPR) is declared a National Reserve on 28 June 1997 by a Royal Decree No. 50/97. It has been designated with the aim of future development for educational purposes, wildlife conservation, and tourism, as well as bringing benefits to local people. It is the largest site in the Middle East, considered a habitat for the Arabian Gazelles. The Nature Park Reserve is in the Wilayat of Al Kamil W'al Wafi in the Governorate of South Al Sharqiyah in the south of Oman at elevations vary from 175 - 255 m above sea level, at about 310 km from Muscat, the capital city of Oman and 57 km from Sur (**Figure 1**). The park covers an area of 220 square kilometers. About 170 km² of it is dominated by *Vachellia tortilis* forests. The sampling area for the destructive work was chosen at the edge of the reserve and permission was obtained for the research purpose.

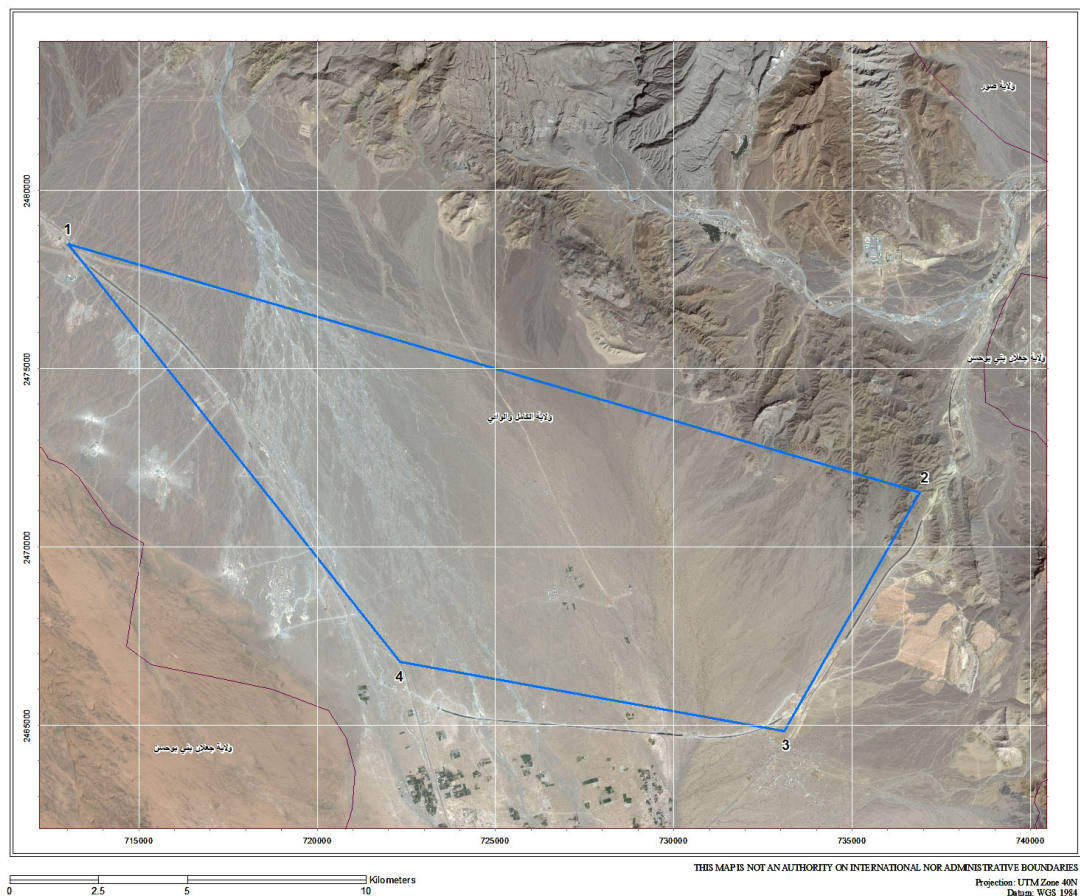


Figure 1. Location of study area.

2.2. Climate of the Study Area

The temperature is low during winter (Oct-Mar), while in summer, it reaches more than 40°C. According to the nearest meteorological station in the area, the average annual temperature varies between 27.629°C and 29°C (**Figure 2**).

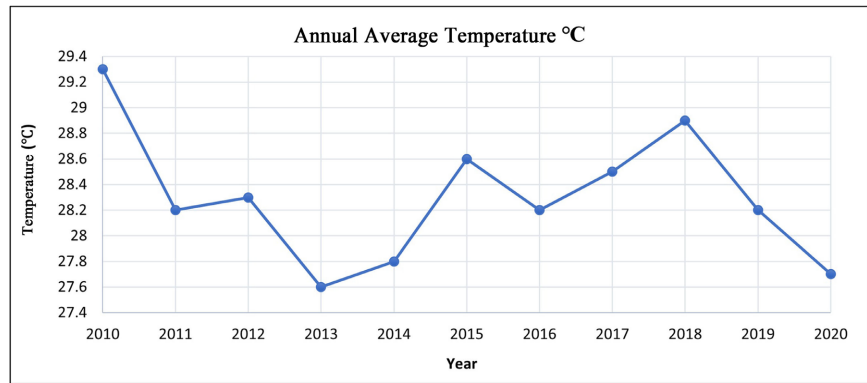


Figure 2. The annual average temperature at study area. (Source: Civil Aviation Authority, 2020)

2.3. Sampling Design & Tree Measurements

Prior to the research work, three site visits were made to the area during the summer period (April-May 2021), two of them specifically to the proposed gas pipeline area. The purpose of these visits was to see the density of *Vachellia* trees along the proposed line, as well as to get an idea about the background environment and to discuss the sampling strategy with reserve staff.

An inventory data of trees was made by establishing circular plots of size 12.5 m × 12.5 m to be used for destructive sampling at eight different locations where *Vachellia* trees are available as shown in **Figure 3**. The plots were laid in the areas along the line where there are *Vachellia tortilis* trees. The coordinates of each plot were taken using Global Positioning System (GPS). For each tree inside the plot, Diameter at stump height (DSH), tree height and crown area (CA) were measured. Since the majority of the trees in the study area have branches at 30 cm and below, the circumference of each tree was measured at 30 cm. A total of 45 trees were measured in all eight plots.

DSH was measured using a measuring tape, and Crown Area (CA) and tree height (H) were measured using a clinometer. After all measurements were taken for each tree, plastic cards with identification numbers were put on the tree for further identification and harvesting.



Figure 3. Study site showing the sampling plots.

2.4. Preparation for Destructive Sampling Work

Before destructive sampling work started, the inventory data of 45 trees in 8 plots

were used to select the trees to be harvested from each plot in the area.

According to the diversity of DSH and height measurements of the 42 trees, the trees were classified into 3 main DSH classes as shown in **Figure 4** below.

- Below 40 cm
- 41 - 63 cm
- Above 63 cm

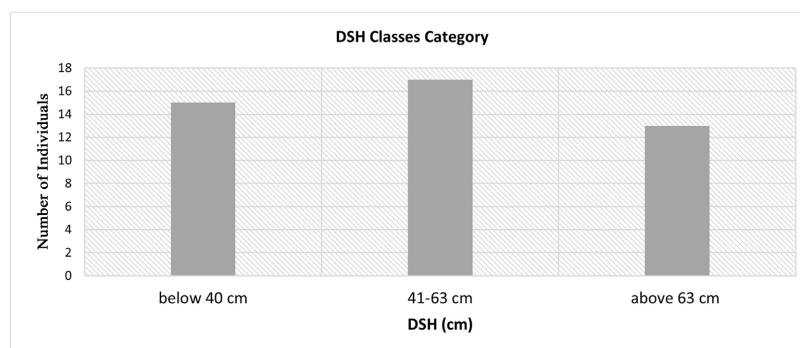


Figure 4. DSH classes of *Vachellia tortilis* in the area.

2.5. DSH Classification

Twenty *Vachellia tortilis* trees were randomly selected, taking into consideration DSH diversity among all trees. The 20 trees were among different classes, as shown in **Table 1** below.

Table 1. DSH Classes of *Vachellia tortilis* species in the study area.

Types	DSH classes (cm)	No of Individuals	No of harvested trees	Harvested trees identification numbers
Young	Below 40	15	6	11, 22, 28, 34, 41, 43
Pole size	41 - 63	17	9	6, 8, 18, 19, 21, 24, 31, 32, 45
Standard	above 63	13	5	2, 7, 16, 26, 36

2.6. Destructive Sampling and Biomass Determination

Before the work, meetings were held in the field to discuss the destructive sampling guidelines with the team to ensure everyone understood the procedure. The work team included an excavation machine driver, two workers, and a four-wheel car driver. Plastic bags, plastic containers, 300 kg spring balance, 160 kg weighing balance, two electronic balances, ropes, GPS (Global Positioning System), permanent markers and a stapler were used during the task. Twenty minimum trees within 25 m buffer zone of the proposed gas pipeline were marked according to the post-classification. The soils were scrapped and removed around the marked tree roots to prepare for excavation. The trees were uprooted by using an excavation machine. Then the tree was weighed using 300 kg spring balance and the weight was recorded on separate paper sheet. The trees were cut into small parts (roots, stems, branches, and twigs/leaves) using a Chain saw (**Figure 5**).



Figure 5. Destructive sampling steps.

Sub-samples were taken from every part (approximately 250 g - 300 g) based on fresh weight of each tree by cutting using hand saw and weighing in 50 g scale balance. Finally, the sub-samples were transferred in plastic bags and plastic containers to the biology laboratory at Sultan Qaboos University for assessment.

2.7. Laboratory Work and Total Biomass Determination

All sub-samples were weighted in the electronic balance in the lab, and the data were recorded. Sub-samples from each part of the trees were dried in the oven at temperatures ranging from 70°C to 105°C for 3 days till a constant weight was obtained. The oven-dried weights of the subsamples were recorded immediately after removal from the oven and used to estimate the fresh-weight ratio. Based on the literature, it was multiplied by the represented estimation fraction of each part of the tree (stems, branches, twigs, leaves) from the whole tree to determine their respective dry weight. Finally, the total biomass estimation was calculated as the sum of the dry weight of each part. (Figure 6)

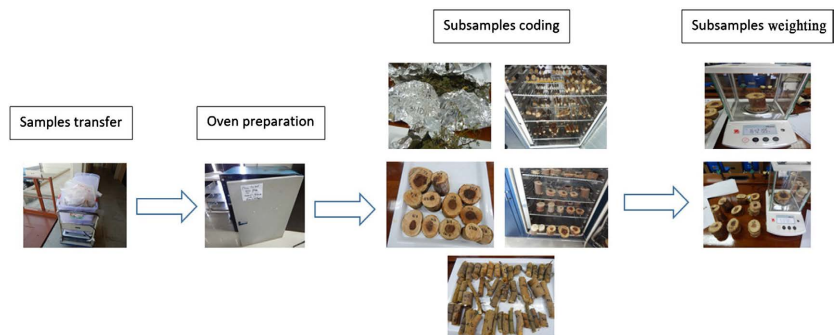


Figure 6. Sub-sample preparation and biomass estimation in the lab.

2.8. Statistical Analysis

To establish the model, we conducted an initial investigation using linear regression to evaluate the relationships between the measured biomass and the predictor variables (DSH, CA, H), assessing their correlations with each other and with biomass. Based on these correlations, DSH and CA were selected as the primary variables for analysis. Consequently, all further analyses were focused on DSH and CA.

2.8.1. Hypothesis Testing

A hypothesis test was formulated to assess the significance of the relationships between biomass and the variables with the strongest correlations. The null hypothesis (H0) posited that the regression coefficients for biomass, DSH, and CA were equal to zero, while the alternative hypothesis (H1) posited that at least one of these coefficients was not equal to zero.

We tested multiple models with different combinations of the predictor variables and transformations, including:

- **Model A:** DSH, CA, with constant = 0
- **Model B:** DSH, CA, with constant \neq 0
- **Model C:** DSH only, with constant = 0
- **Model D:** log-transformed DSH
- **Model E:** log-transformed DSH and log-transformed CA, with constant = 0

Multiple regression analyses were then performed to evaluate the relationship between observed biomass and the predictor variables, generating regression statistics for each model. Variance analysis and P-values were checked to assess model significance.

The best-fitting allometric models for estimating above-ground biomass (AGB) were selected based on the highest Coefficient of Determination (R^2), lowest Mean Square Error (MSE), and significant P-values.

2.8.2. Selecting the Best Equation

Each model, A, B, C, D was subjected to multiple regression analysis to determine the best-fitting allometric models for estimating biomass. Model performance was evaluated using three key statistical tests:

R^2 (Coefficient of Determination): Measures the proportion of variability in the biomass that can be explained by the model.

A higher R^2 indicates a better model fit.

MSE (Mean Squared Error): Quantifies the average squared difference between observed and predicted biomass values.

A lower MSE suggests better predictive accuracy.

P-value: Assesses the statistical significance of the model coefficients.

A p-value less than 0.05 indicates that the relationships observed are statistically significant.

3. Results and Discussion

3.1. Results

3.1.1. Model Development & Regression Analysis

Table 2 shows five allometric equations which were developed and tested. We explored the relationships between the biomass of the trees and the selected independent variables, that is, DSH, H, and CrA to identify the nature of the relationships. The DSH and CrA, DSH and H showed a non-linear relationship. The logarithmic transformation allowed for the control of significant variations in the data. The models were built with different independent variables to provide a range of options that can be used by researchers depending on the available information from tree inventories. The multiple regression analysis, performed on different combinations of predictor variables, produced a range of models, each with varying degrees of predictive power. The performance of each model was assessed using three key statistical tests: Coefficient of Determination (R^2), Mean Square Error (MSE), and P-value.

Table 2. Summary of developed allometric equations.

Model Code	Model Form	R^2	MSE	P-value
A	$AGB = 126.271 * DSH + 7.466 * CrA$	0.831	5252	1.81E-07
B	$AGB = 25.698 + 1.664 * DSH + 7.279 * CrA$	0.645	5100	0.000151
C	$AGB = 255.5 * DSH (m)$	0.783	6759	1.51E-07
D	$AGB = \log DSH$	0.98	1.32	6.32E-17
E	$ABG = 1.278 * \log DSH + 1.813 * \log CrA$	0.97	0.114	5.48E-14

3.1.2. Model Performance Evaluation

Model A ($AGB = 126.271 * DSH + 7.466 * CrA$)

This model showed a strong R^2 value of **0.831**, meaning that DSH and CrA were 83.1% of the variance in AGB, which was highly significant (**P-value of 1.81E-07**). However, the **MSE** of 5252 suggests that there is still room for improvement in the prediction accuracy of this model. It indicates that 83.1% of the variance in AGB can be explained by DSH and CrA. While the model is significant, the moderate MSE suggests room for improvement in prediction accuracy.

Model B ($AGB = 25.698 + 1.664 * DSH + 7.279 * CrA$)

With a P-value of 0.000151, this model is statistically significant. The MSE (5100) is slightly lower than in Model A, suggesting marginally better prediction accuracy, yet its R^2 value (0.645) shows that only 64.5% of the variance in AGB is explained by DSH and CrA, making it less predictive overall than Model A.

Model C ($AGB = 255.5 * DSH$)

Model C, using DSH as the sole predictor, yielded a significant P-value of 1.51E-07 and an R^2 of 0.783, explaining 78.3% of the variance in AGB. However, with an MSE of 6759, this model demonstrated the highest prediction error among

the linear models, indicating that DSH alone does not provide optimal prediction accuracy for AGB.

Model D (AGB = log DSH)

This model was highly effective, with an extremely low P-value ($6.32E-17$), and an R^2 of 0.98, meaning 98% of the variability of AGB was explained by log transformed DSH. The MSE was also remarkably low (1.32) highlighting model D as the best predictive for AGB among the options evaluated.

Model E (AGB = 1.278 * log DSH + 1.813 * log CrA)

Model E produced a highly significant P-value of $5.48E-14$, an exceptionally low MSE (0.114), and an R^2 of 0.97, capturing 97% of the variance in AGB. Although its predictive power is nearly as strong as Model D, Model E demonstrated the lowest MSE, suggesting that including both log-transformed DSH and CrA in the model enhances precision.

Overall, Model D, with the highest R^2 (0.98) and a low MSE (1.32), was identified as the most predictive model for estimating AGB. Model E, with an R^2 of 0.97 and the lowest MSE (0.114), also showed strong predictive power, particularly in precision. These results indicate that models incorporating log-transformed DSH (and in the case of Model E, log-transformed CrA) are the most effective for accurate AGB estimation.

3.2. Discussion

The development of species-specific allometric equations for estimating above-ground biomass (AGB) of *Vachellia tortilis* in this study has provided valuable insights into the predictive capacity of various tree measurements. Among the five models tested, **Model D** (log-transformed DSH) emerged as the most effective for biomass estimation, with an R^2 of **0.98** and an **MSE** of **1.32**. This aligns with findings from other studies demonstrating the effectiveness of logarithmic transformations in allometric scaling. For instance, [El-Naggar and El-Din \(2021\)](#) provided species-specific allometric equations for *Acacia tortilis* (now renamed as *Vachellia tortilis*) Acacia in arid regions of Egypt, supporting the utility of log-transformed variables in biomass estimation.

3.2.1. Comparison to Other Studies

Compared with other recent allometric models, such as those developed for Acacia species in East Africa, there is a clear trend favoring site- and species-specific models for improving biomass estimation. [Mao et al. \(2023\)](#) emphasized the importance of localized equations for Acacia woodlands, while [Moussa and Brown \(2019\)](#) highlighted the effectiveness of localized allometric models for Acacia species in semi-arid regions of Kenya. The high R^2 values and low MSE seen in Models D and E in this study (0.98 and 0.97, respectively) further underscore the utility of localized equations for dryland species like *Vachellia tortilis*, as opposed to more generalized pantropical models, which often show lower predictive accuracy in specific ecosystems.

3.2.2. Role of Crown Area in Improving Model Accuracy

The inclusion of crown area (CA) in the models, particularly Models A and B, also reflects a growing recognition of the role of crown dimensions in biomass prediction. This is supported by recent work by Kang and Su (2016), who developed allometric equations incorporating crown attributes for Acacia plantations in Kenya, highlighting the importance of these dimensions in biomass estimation. Given the environmental stressors often encountered in arid and semi-arid regions, it is not surprising that the inclusion of Crown Area (CrA) alongside DSH significantly improved model performance.

Ultimately, the findings of this study contribute to the expanding body of research advocating for the development of species-specific allometric equations, especially in dryland ecosystems. As demonstrated by the superior performance of Model D, the use of log-transformed variables, coupled with site-specific data, leads to more accurate predictions of biomass, which is crucial for carbon accounting and ecological management in arid environments.

4. Conclusion

Species-specific equations with the log of two measurable parameters (DSH and CA) predict biomass more precisely in most instances than a general model. Overall, Model D, with the highest R^2 (0.98) and a low MSE (1.32), was identified as the most predictive model for estimating AGB. Model E, with an R^2 of 0.97 and the lowest MSE (0.114), also showed strong predictive power, particularly in precision. These results indicate that models incorporating log-transformed DSH (and in the case of Model E, log-transformed CrA) are the most effective for accurate AGB estimation.

The observed significance of log-transformed models can be attributed to the relatively high variability within the data, which was partly due to the aridity of the study area and differences within the sample categories.

The models developed in this research fill a critical gap in estimating AGB in dry land in Oman and other countries with similar ecological and climate conditions. Effective and sustainable natural resource management in protected areas needs to be done. The decision makers should take decision based on reliable and scientific information about conservation priorities in nature reserves in Oman. The most accurate equations originally developed from this work will help in carbon trade discussions and in terms of developing climate change mitigation strategies and CO₂ emission reduction and achieving a net zero plan in the Sultanate of Oman.

Acknowledgements

We would like to thank OQ Oman Company for their support in handling destructive sampling expenses and logistics. Also, we would like to thank the Department of Biology, College of Science at Sultan Qaboos University, for their logistic support throughout the research period. We also thank Dr. Abdullah Al-

Nadabi and Mrs. Munera Al Habsi from the Department of Biology, College of Science at SQU.

Funding

This work was funded by OQ Company and supported by the Environment Authority.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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