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Statistical Evaluation of Outdoor Field Hockey Penalty Corners

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ABSTRACT
Penalty corners stand out as pivotal goal-scoring opportunities in field hockey, crucial to a team's triumph. This study harnesses data from women's collegiate field hockey games to formulate a statistical model predicting the likelihood of scoring a penalty corner, contingent on the strategies deployed. Various machine learning algorithms are compared to ascertain the most predictive model and to dissect the paramount factors influencing penalty corners. The XGBoost model emerges superior, boasting an area under the curve (AUC) score of 0.667 on out-of-sample observations. With other predictors held constant, the model reveals that drag flicks, sweep shots, and deflections are positively associated with goal occurrences, while, intriguingly, direct shots—despite their prevalence—are negatively associated with scoring probability.

KEYWORDS
College Sports; K-Nearest Neighbor; Lasso; Quantitative Analysis; Random Forest; Sporting Strategy; Sports Analytics; XGBoost

INTRODUCTION

Field hockey, originating from ancient Greece, has sustained its prominence through centuries and currently boasts over 250 women's collegiate programs actively competing[1]. This sport engages two teams, each consisting of eleven players, in a strategic contest to score by maneuvering a ball into the opponent's goal using specially crafted sticks. Unlike ice hockey, field hockey is played on either natural or artificial grass surfaces, within a field measuring 91.4 meters by 55 meters. Notably, goals are only valid if scored from within a defined area, termed the striking circle[2]. The strategic complexities and widespread popularity of field hockey underscore the significance of analytical studies within the sport.

Our analysis focuses on penalty corners. With approximately one-third of goals occurring on penalty corners in high-level women's field hockey matches, and the North Carolina Tar Heels, winner of five of the last seven national championships, dedicating twenty percent of their practice time to them, it is clear that penalty corners are pivotal to match outcomes[3, 4]. A penalty corner is awarded to the attacking team when a defender commits a foul within the striking circle. During this play, an inserter hits the ball from the end line into the field, while teammates, positioned above the penalty circle by rule, endeavor to control the ball and score. Conversely, the defensive team positions four outfield players and a goalkeeper behind the goal line, who may move only after the inserter has struck the ball, aiming to thwart the attackers[2].

Some studies have examined strategic approaches to penalty corners in outdoor field hockey. Laird and Sutherland[5] analyzed the 1998 field hockey World Cup and found most successful goals resulted from straight shots, either flicked

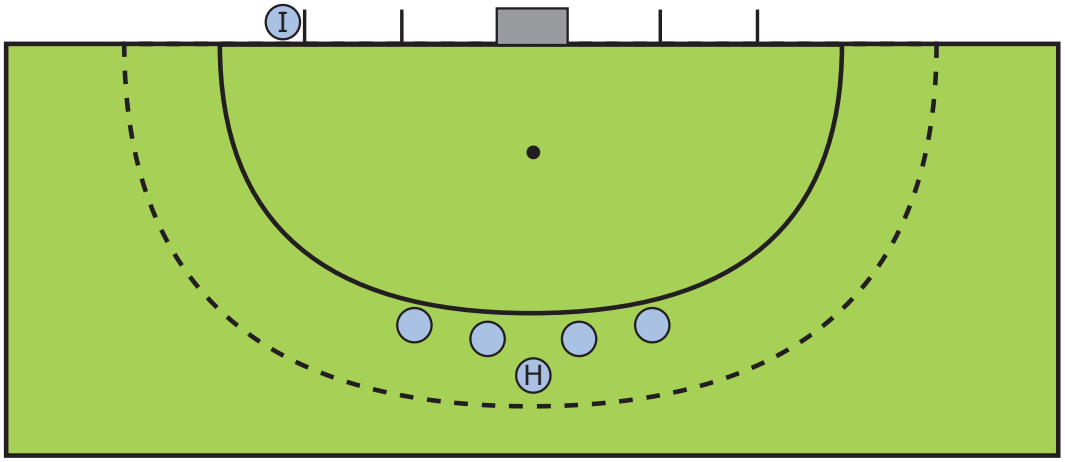

Figure 1. A diagram of a possible offensive setup during a field hockey penalty corner, with blue circles representing attackers. The inserter ("I") puts the ball into play by passing it to a teammate positioned outside the shooting circle, as required by the rules. The ball typically flows to the hitter ("H"), who then plays the ball toward the goal, often after a teammate stops the ball just outside the circle. Other offensive players execute roles such as stopping the ball, screening defenders, or positioning for rebounds or deflections.

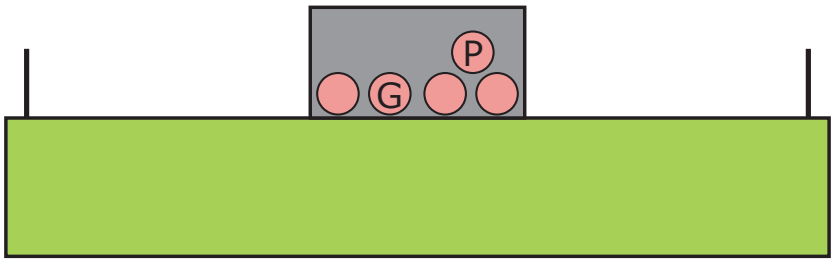

Figure 2. A diagram of a possible defensive setup during a field hockey penalty corner, with red circles representing defenders. By rule, a maximum of five defenders, including the goalkeeper ("G"), begin behind the end line until the ball is inserted. In this instance, all defenders are positioned within the goal. Also shown is the post defender ("P"), who plays a key role in stopping shots near the goal. While most defenders sprint toward the attackers upon insertion, the post defender typically remains near the goal (either just in front or behind the goalkeeper) to provide an additional layer of defense.

or undercut. Kerr and Ness[6] compared push-in performers of different experience and advised coaches to maximize drag distance and utilize a blend of simultaneous and sequential segment rotations to optimize accuracy and ball speed, thereby maximizing drag speed. Lopez De Subijana et al.[7] analyzed the kinematics of drag flicks, a prevalent shot technique during penalty corners, and observed distinct differences in stance width and explosive movement of the stick and pelvis across varying skill levels. Klatt et al.[3] determined that adaptive decision-making after ball insertion can enhance scoring opportunities during a penalty corner. Lord et al.[8] discovered variations in team strategy on penalty corners, contingent upon their physical capabilities, in 2019 men's and women's International Hockey Federation Pro League matches. Notably, no studies have scrutinized penalty corners using both statistics and machine learning to identify areas for improvement. Our analysis will explore a wide spectrum of strategic choices, including shot technique, shot location, and goalie positioning.

In the broader domain of sports akin to outdoor field hockey such as soccer and indoor field hockey, numerous studies have employed machine learning models and statistical testing to extract valuable insights into sporting strategy. Alcock[9] analyzed the probability of scoring a free kick in elite international women's soccer, advocating for shots in situations with minimal goal distance and a favorable angle. Vinson et al.[10] modeled the likelihood of scoring a penalty corner in women's professional indoor field hockey competitions, pinpointing the goalkeeper's strategy—either holding the goal line or confronting attackers—as a crucial predictor. Maneiro et al.[11] discerned notable differences in soccer corner kick tactics between the men's and women's 2018 and 2019 World Cups, respectively. Anzer and Bauer[12] inves-

Variable	Description	χ^2 test p-value
Goal	Indicates if the attacking team scored during the penalty corner	
Deflection	Indicates if the ball changed direction off an attacker toward the goal	0.034*
Direct Shot	Indicates if an attacker hit the ball directly toward the goal	0.130
GK Up	Indicates if the goalkeeper was standing upright while defending	0.214
Post in Front of GK	Indicates if the post defender was positioned in front of the goalkeeper	0.297
Drag Flick or Sweep	Indicates if the shot used a flicking or sweeping motion rather than a standard hit	0.023*
Shot Bottom	Indicates if the shot was aimed at the lower third of the goal	0.052
Shot Info	Indicates if there was a recorded shot on goal during the penalty corner	0.265

Table 1. Descriptions of explanatory variables and the p-values of their association tests with the Goal variable.

tigated momentary scoring probability in top-tier German league men's soccer matches, identifying an extreme gradient boosting model as optimal for unseen data. Of these, Vinson et al.[10] aligns most closely with our work, though it concentrates on professional indoor field hockey rather than collegiate outdoor field hockey. While most pertinent papers have primarily focused on professional sports, our study seeks to shed new light on field hockey and women's collegiate sports.

Our contributions to the field are twofold. First, utilizing qualitative information regarding strategies and techniques employed during a field hockey penalty corner, we hypothesize that the likelihood of scoring a goal can be predicted. Second, we seek to provide insights into the most effective tactics utilized during these set pieces. To provide a brief overview, we utilize data supplied by a women's collegiate field hockey team on penalty corners and compare various machine learning methods to identify the most predictive model. Subsequently, we offer a potential interpretation of the findings within the context of field hockey strategy and gameplay.

DATA

The data for this study was provided by the University of Connecticut NCAA Division I women's collegiate field hockey program. Specifically, the team utilized Hudl SportsCode^{TM}, a sports analysis software, to examine occurrences during a given penalty corner, recording various categorical traits of the play, including goalkeeper positioning, defensive formation, and shot technique, among other variables. The analyses were subsequently converted into a tabular dataset. The penalty corners included in the study span several games from the 2021 season, all involving either the University of Connecticut field hockey team or a scouted opponent. Given that the original intent of the data was to track qualitative traits in a non-statistical analysis, the initial dataset occasionally presented issues for performing statistical methods, such as containing two values in a single data cell. In such instances, we consistently utilized the last value of the cell for analysis. After cleaning, we aimed to use the data to discern strategies that maximize the expected chance of scoring a goal during outdoor field hockey penalty corners.

The cleaned data contains $n = 309$ observations, each corresponding to a penalty corner occurrence. Among these 309 penalty corners, 42 (13.59%) resulted in a goal. Each observation contains qualitative insights of the occurrences on the play. These qualitative variables were converted to binary variables, which better allows statistical analysis on the data. The outcome variable of interest is Goal, indicating whether a penalty corner sequence resulted in a goal. **Table 1** presents a list of explanatory variables that can potentially be used to predict scoring.

Figure 3 showcases mosaic plots that effectively visualize the relationship between different strategies and goal scoring in field hockey. These plots use the vertical axis to represent the occurrence of scoring, while the plot width indicates the sample size of each grouping[13]. For enhanced clarity, the total number of observations within each group is also provided. A careful analysis of these plots reveals a discernible positive correlation between the probability of scoring and strategies such as deflections, drag flicks, sweep shots, and targeting the lower part of the net. This suggests that teams employing these tactics can expect a higher chance of scoring. In contrast, a negative relationship is evident between scoring chances and the use of direct shots, indicating that they may be less effective in scoring goals.

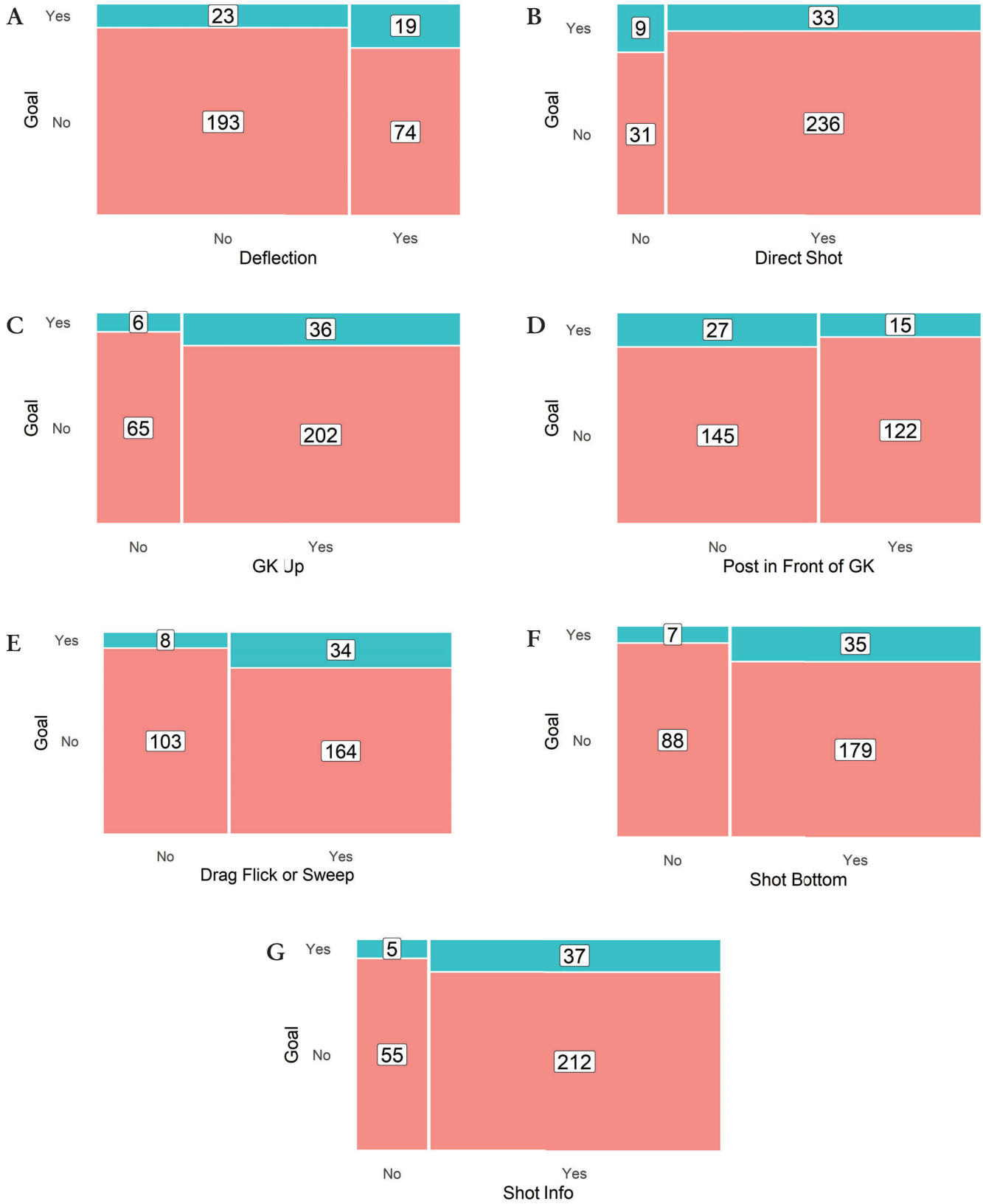

Figure 3. Mosaic plots illustrating the relationship between goal scoring and various explanatory variables. The height of the blue bars represents the proportional difference in goal scoring associated with the presence or absence of a given strategy, while the width reflects how frequently that strategy was employed. Subplots (A–G) correspond to the seven strategies analyzed, with axes labeled in each panel.

Also reported in **Table 1** are the p-values from χ^2 tests for all the explanatory variables, assessing their associations with Goal. "Deflection" and "Drag Flick or Sweep", with p-values of 0.034 and 0.023 respectively, demonstrate statistically significant associations with scoring. Conversely, variables such as "Direct Shot", "GK Up", "Post in Front of GK", "Shot Bottom", and "Shot Info", exhibit p-values ranging from 0.052 to 0.297, indicating no statistical significance in their association with scoring. The variables in this table provide a departure point of using advanced machine learning approaches to predict scoring during penalty corners.

METHODS

In our study, we focused on building machine learning models to accurately predict the occurrence of a Goal during penalty corners in field hockey. We employed a variety of modeling algorithms, each offering a distinct approach to predicting scoring chances. These include lasso logistic regression[14], K-nearest neighbor[15], random forest[16], and extreme gradient boosting (XGBoost)[17].

Each model's tuning parameters were carefully selected through a non-nested 5-fold cross-validation process[18], with stratification based on the Goal outcome. In addition to the stratification, all penalty corners from the same game were assigned to the same fold to prevent data leakage. For the lasso logistic regression, we explored a wide range of penalty parameters C, from 10^{-5} to 10^{5}, and incorporated second-degree interactions between predictors. The optimal performance was achieved with a penalty of $C = 1$. Similarly, the K-nearest neighbor model was tuned across a spectrum of K values, from 1 to 101, again considering second-degree interactions. The model reached its peak effectiveness when K was set to 49.

We configured the random forest model with 500 trees and undertook a tuning process to optimize various parameters. These parameters included the minimum tree depth sample size (ranging from 1 to 8), the impurity metric (Gini vs. entropy), the minimal number of samples required for a split (either the default value of 2 samples or a range from 10% to 25% of the data), and the maximum number of features to be considered in a tree (options being square root, $\log_2$, or all available features). The optimal performance was achieved using the Gini criterion, a maximum depth of 5, a minimum of 10% of the data samples per split, and considering the square root of the total number of features in a tree.

The XGBoost model underwent a similar tuning process. Similarly to random forest, the model was fixed to 500 trees. We sought the best settings for maximum tree depth (from 1 to 8), learning rate (between 0.05 and 0.30), regularization alpha (between 0 and 10), and regularization lambda (also between 0 and 10). The best results were obtained with a maximum depth of 2, a learning rate of 0.05, a regularization alpha of 0.5, and a regularization lambda of 10.

Out-of-sample predictions from 5-fold cross-validation were computed for the probability of scoring a goal during each penalty corner given the predictors. This method involves dividing the data into five parts, using four for training our model and one for testing its predictions. This approach helps ensure our model's predictions are reliable when applied to new, unseen data. We focused on the best-performing model from each method and examined its effectiveness using Receiver Operating Characteristic (ROC) curves. These curves are crucial for understanding a model's ability to distinguish between two outcomes—in our case, whether a goal is scored or not.

The area under the curve (AUC) of the ROC curve serves as a robust metric to numerically evaluate the predictive performance of classification models[19]. The AUC quantifies the overall ability of the model to discriminate between the binary classification of goal outcome during a penalty corner. An AUC of 1.0 indicates perfect predictive ability, while an AUC of 0.5 suggests no predictive ability, akin to random guessing[20]. In our study, a higher AUC indicates that the model has a higher probability of ranking a randomly chosen positive instance (a scored goal) higher than a randomly chosen negative instance (a missed goal). Thus, in comparing the predictive power of the four methods, the model with the highest AUC would be considered the most proficient in accurately predicting the occurrence of a goal during a penalty corner, providing a valuable metric in the evaluation and comparison of model efficacy.

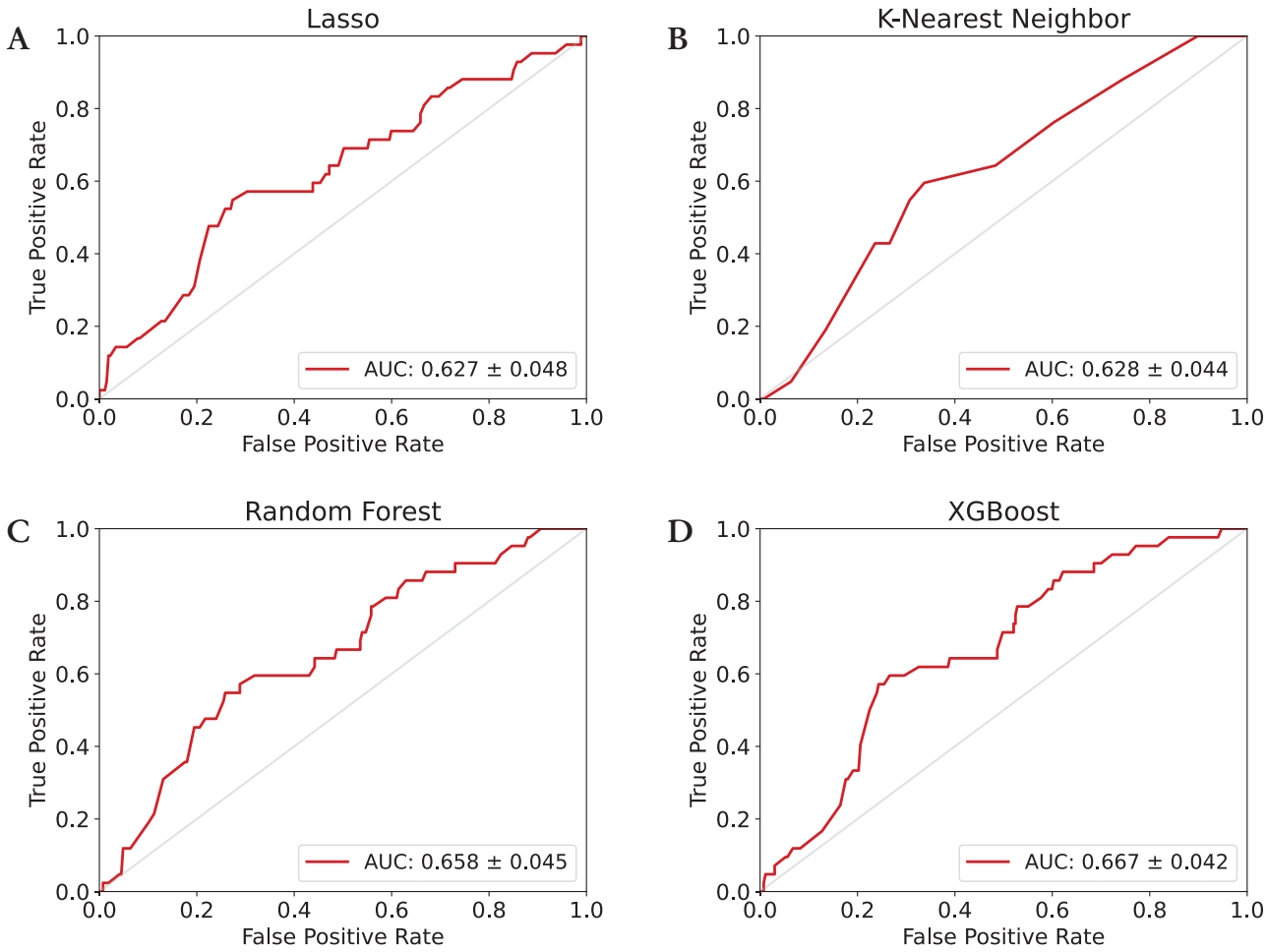

Figure 4. ROC curves for four classification models. Red lines show the overall ROC curve across all out-of-sample predictions, with higher AUC values indicating better classification performance. Each plot also displays the standard error of the AUC, providing a measure of method stability. Subplots (A–D) correspond to: (A) Lasso, (B) K-Nearest Neighbor, (C) Random Forest, and (D) XGBoost, with axes labeled in each panel.

Figure 4 displays the ROC and AUC score derived from out-of-sample predictions using the four methods. In addition to the AUC score, a standard error is also included, calculated using the nonparametric method, to better indicate the stability of each model[21]. XGBoost emerges superior, achieving an AUC of 0.667. Given the relative success of XGBoost compared to the other modeling techniques, it is selected for further analysis. An AUC of 0.667 indicates a moderate ability of the XGBoost algorithm to predict the goal scoring chance of unseen observations. While there may be additional predictors not included in our dataset or model that could enhance the AUC score, the model nonetheless identifies some predictive relationship between the predictors and response, deeming it adequate for the purposes of this study.

RESULTS

We have chosen to present the results from the XGBoost model as it demonstrates superior performance with the highest AUC among all the models we tested. The feature importance scores, derived from XGBoost's built-in functionality, are illustrated in **Figure 5**. In this chart, features are arranged in order of their importance; those with higher importance values are placed on the top, while those with lower importance are on the bottom. A key observation from this analysis is the paramount importance of whether a deflection occurred during the penalty corner sequence, which holds the highest feature importance value at 0.24. Following closely are factors such as the goalkeeper's alignment relative to the post defender (0.23), a direct shot taken (0.18), and shots aimed toward the bottom of the net

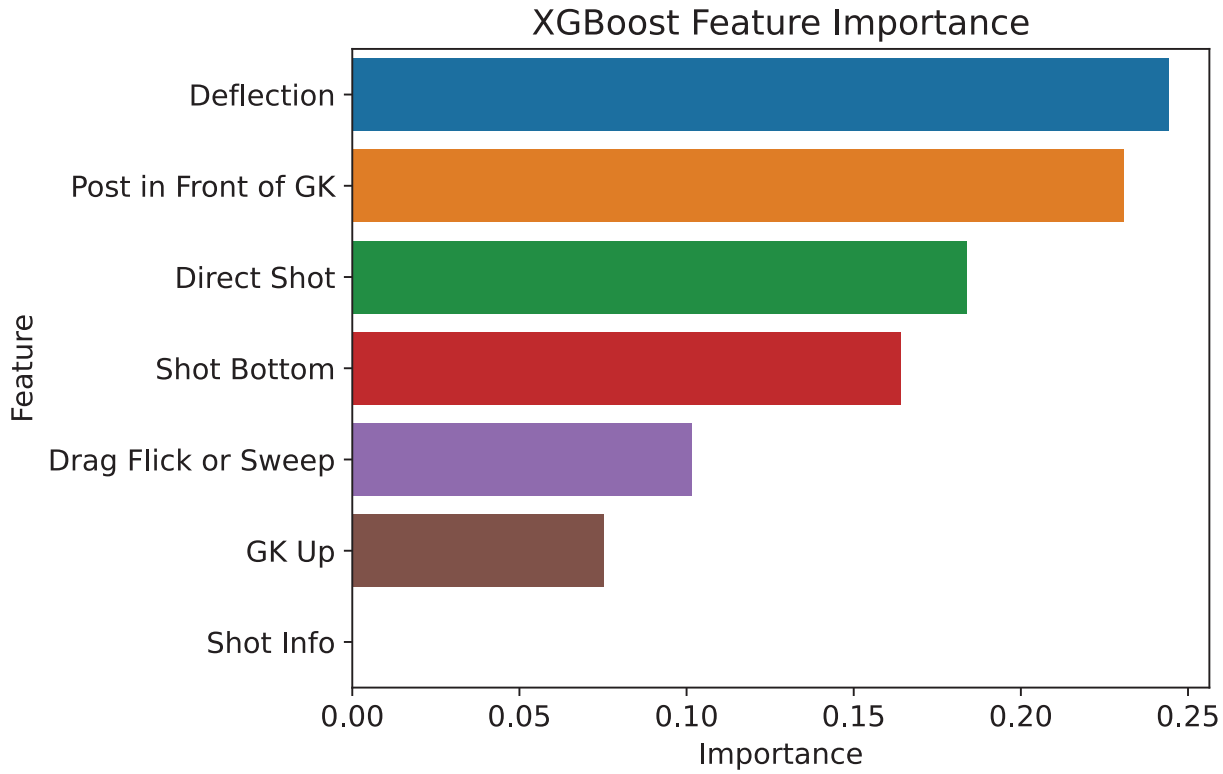

Figure 5. Feature importance scores from the XGBoost model. The plot shows how much each variable contributed to the model's predictions, with higher values indicating greater magnitude of influence on the prediction of whether a goal was scored, regardless of whether the variable increased or decreased the predicted likelihood.

(0.16). Other features with less impact include the use of drag flick or sweep shot techniques (0.10) and whether the goalkeeper adopts an upright stance (0.08). Interestingly, the model did not use the feature that indicates if a shot occurred during the penalty corner (0.00). These results provide insightful perspectives on the factors most influential in determining the success of a shot during a penalty corner in field hockey.

While the feature importance values derived from the XGBoost model offer valuable insights, they fall short in one crucial aspect: they do not indicate the direction of the relationship between each feature and the target variable. Simply put, the feature importance plot does not indicate whether the strategies used in goal scoring have a positive or negative impact on the likelihood of scoring. To address this gap, we turn to SHAP (SHapley Additive exPlanations) values[22]. SHAP values provide a more nuanced view by detailing how each predictor influences the target variable, thereby illuminating the direction of their impacts. This approach allows us to understand not only which features are important, but also how they positively or negatively affect the chances of scoring in field hockey, as indicated by our model.

Figure 6 illustrates the variable impacts on scoring from our analysis. Given that our predictors are binary, a red point on this plot signifies that a particular strategy was employed during the play, while a blue point indicates its absence. This color coding helps us discern that the use of drag flick or sweep shot techniques is strongly positively associated with an increased chance of scoring. When these techniques are executed, they significantly boost the predicted likelihood of scoring. Conversely, their absence is linked to a considerable decrease in scoring probability. Similarly, strategies such as directing shots toward the bottom of the net and deflecting shots toward the net also show a positive relationship with scoring success. Interestingly, the goalkeeper's adoption of an upright stance, while having a weaker influence, still positively correlates with scoring during a penalty corner. On the flip side, strategies that tend to reduce scoring chances include the post defender aligning in front of the goalkeeper and taking direct shots. Both strategies ex-

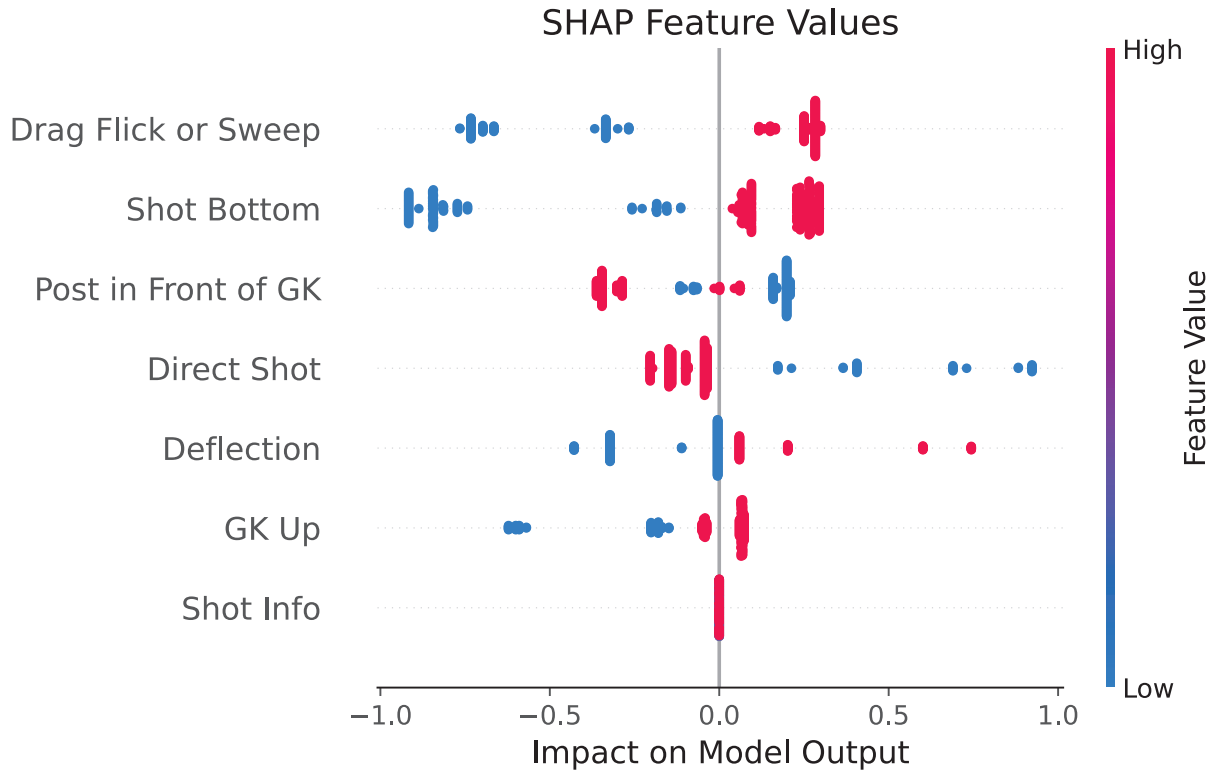

Figure 6. SHAP values from the XGBoost model. The plot illustrates how each binary feature influenced predictions of goal scoring. Each point represents a single observation, with red indicating that the feature occurred and blue indicating that it did not. Points farther from zero indicate a greater impact on the model's prediction, with the direction reflecting whether the feature increased or decreased the predicted likelihood of a goal.

hibit a moderate negative association with scoring. As also noted in **Figure 5**, the feature indicating if a shot is taken during the penalty corner was not used by the model and therefore has no impact on the chances of scoring, according to our model.

Our findings offer valuable insights for field hockey coaches. Teams may improve their scoring effectiveness by strategically focusing on deflections, drag flicks, and sweeps aimed at the lower regions of the net. Conversely, for defense, teams may reduce the opposition's scoring efficiency by aligning their post defender in front of the goalkeeper and the goalkeeper adopting a downward stance. A noteworthy aspect of our analysis is the negative relationship between direct shots and successful goal attempts. Our model suggests, with all other variables constant, a reduced frequency of scoring from direct shots. This may seem surprising, but it is supported by our initial dataset. Goals were scored on 22.5% of the 40 penalty corners without a direct shot, as opposed to only 12.3% of the 269 penalty corners with a direct shot. Therefore, teams might consider exploring potentially more effective strategies if direct shots are identified as the root cause of suboptimal goal scoring opportunities.

DISCUSSION

In the endeavor to predict the likelihood of scoring during a field hockey penalty corner, this study embarked on the creation and comparison of various machine learning models, each tailored to the specific events and strategies deployed during the play. Amongst a spectrum of modeling techniques, XGBoost was distinguished as the most potent predictive model, a claim substantiated by its AUC score of 0.667 on out-of-sample data. This model unveiled a positive association between the probability of scoring and the utilization of the deflection shot type, as well as the drag flick and sweep shot techniques, upright goalkeeper stance, and shots located toward the bottom of the net during penalty corners. Moreover, our findings illuminated a somewhat unexpected and counter-intuitive negative association between the likelihood of scoring and the execution of a direct shot, despite the latter's prevalent deployment in matches. This

particular insight accentuates the opportunity for teams to reevaluate and innovate their penalty corner strategies, potentially exploring alternative techniques that might enhance scoring probabilities.

Concluding the analysis, the research into field hockey penalty corners still harbors substantial potential for further exploration and discovery. With data more meticulously tailored for statistical analysis, it is conceivable that numerous additional predictors could be incorporated into a similar model, including the shot distance, precise player locations during the penalty corner, the prevailing score, and the residual time in the game. An additional research avenue could involve addressing a multiclass classification problem, where the response variable encompasses not only the occurrence of a goal, but also other outcomes such as missed shots, saved attempts, or turnovers during the play. It is also pertinent to note that the data only encompasses games from a single season of a specific field hockey program and some scouted opponents. Future studies, armed with data spanning a more expansive array of collegiate women's field hockey teams, may yield even more compelling and robust results.

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PRESS SUMMARY

Penalty corners stand out as pivotal goal-scoring opportunities in field hockey, crucial to a team's triumph. This study harnesses data from women's collegiate field hockey games to formulate a statistical model predicting the likelihood of scoring a penalty corner, contingent on the strategies deployed. We find that drag flicks, sweep shots, and deflections are positively associated with goal occurrences, while, intriguingly, direct shots—despite their prevalence—are negatively associated with scoring probability.

Adapting Multiple Imputation for Compositional Survey Data

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ABSTRACT
Compositional data, where each component is a proportion of a whole, presents unique statistical challenges, particularly when incomplete. Multiple Imputation (MI) has become a standard method for imputing incomplete quantitative, ordinal, or categorical data, but there are not any proposed imputation methods for incomplete compositional data that are able to preserve the characteristics of the compositions. We propose methods for imputing compositional data, and use the imputed datasets to conduct analysis on exercise motivation survey data. The novel method will be used to impute missingness in the original dataset, which serves as the basis for the model development. The results of the analysis will be used to evaluate the performance of our proposal against standard methods.

KEYWORDS
Applied Bayesian Statistics; Exercise Motivation; Missing Data; Multiple Imputation; Multivariate Statistics; Survey Methodology

INTRODUCTION

Missing data arises from various sources such as incomplete responses to surveys and errors during data collection. In surveys or measurements where data is compositional, the values for each compositional variable need to sum to a whole, typically 1 or 100%. **Figure 1** is a visual representation of how missingness can look in a dataset that is made up of compositional data. Each bar represents one participant or observation, and each colored section is a different compositional variable. Compositions need to add up to the same sum for each observation, and the lengths of the bars in the figure are constant to represent this relationship. The missingness, identified in the figure by the white gaps outlined by dotted lines, can occur differently from observation to observation. Some observations might have only one missing value like Participant 3, while others have all but one value missing, like Participant 2. Regardless of the amount of missingness present, the sum of all the values in the column (both known and unknown) is held at the known value for the whole. It is important to resolve missingness in order to proceed with most types of analysis.

For any missing value, there is inherent uncertainty about what each of the missing values could be. As a result, it is important that any method used to handle this missing data is able to consider the uncertainty when imputing, or filling in, the missing values. One commonly referenced method for handling missing data is Multiple Imputation (MI), which involves performing several imputations on each missing value to account for the variability that is present.[1, 2] However, conventional MI implementations does not take into account the need to maintain a specific sum across the whole observation.

Within MI, there are several widely-accepted imputation methods for standard numerical data, such as imputation by Bayesian linear regression,[3] predictive mean matching,[4] and random forests.[5] However, there is not currently a pro-

posal for imputing incompletely observed compositions in the statistical literature. Compositional data is a type of multivariate data in which each variable, or component, is part of a whole.[6] Each component individually represents a proportion, and the values in each column are relative to each other. Rather than the typical Euclidean space R^D, the sample space for compositional data is the simplex, a $D-1$ dimensional subspace of R^D due to the summation constraint.[7] These factors complicate the imputation of compositional data.

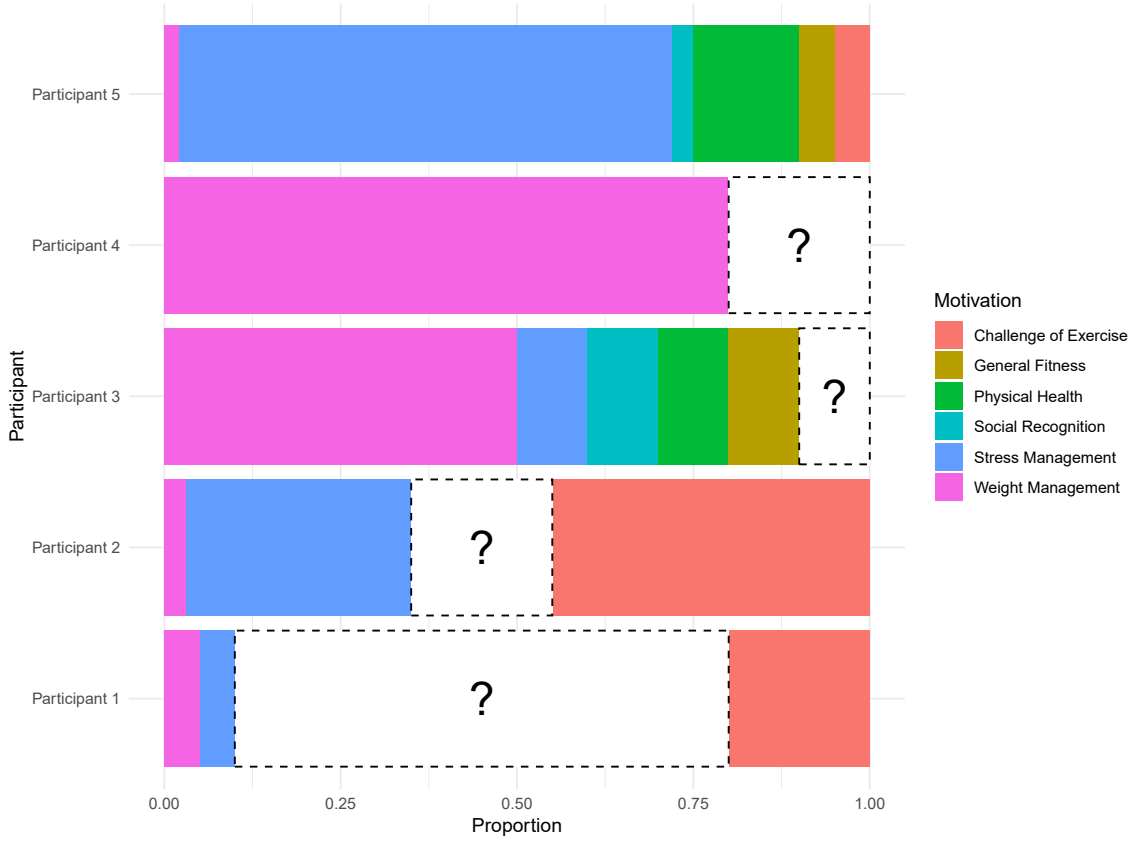

Figure 1. Each bar in this graph represents a participant, and the heights of each bar are the same to indicate a consistent total that needs to be reached. Missing values within a participant need to be imputed, which can be difficult when more than one component is missing.

In this paper, we propose a Scaling method and an Isometric Log-Ratio (ILR) Regression method for imputing incomplete compositional data. The Scaling method is based on the imputation of missing values at the composition component level using multiple imputation, and the subsequent rescaling of the data to maintain a sum of 1 for the whole observation. The ILR Regression method is based on the ILR transformation, which involves using the Isometric Log-Ratio transformation to transform the different components before imputing the missingness at the ILR level for each incomplete observation. With these methods, we address the imputation of missing compositional data. We are not aware of literature addressing the imputation of this particular type of data and we aim to fill that gap with the proposal of these methods.

These implementations will be evaluated in the context of a survey about exercise motivation, in which respondents have assigned percentages to the following exercise motivations in order to capture their relative importance:

1. Managing stress
2. Maintaining or improving weight and/or appearance
3. Gaining social recognition

4. Enjoying the challenge of exercising
5. Improving physical health
6. Maintaining or improving fitness

This paper is structured as follows. In the Background section, we provide information on the missing data analysis and compositional data analysis. In the Data section, we introduce the motivating dataset and discuss the data collection process. In the Methods section, we detail our proposed methods for imputation. In the Simulation section, we explain the process of our simulation study, and present the simulation results in the following section. In the Survey Data Analysis Results section, we present the results of our application of the methods to the motivating dataset. In the Discussion, we discuss the results and suggest potential future work to improve these methods.

BACKGROUND

Missing Data and Multiple Imputation

The preferred method for imputation can vary depending on the characteristics of the data generating process. These characteristics include the missingness mechanism and the nonresponse pattern, both of which concern the underlying reasons for and the distribution of missing data within the dataset. Rubin established a framework for treating missingness as probabilistic.[3] The missingness is represented by an indicator variable matrix R, where $R = 1$ when the value is complete and $R = 0$ when the value is incomplete.[8] The complete dataset, Y_{com}, is made up of its observed (Y_{obs}) and missing (Y_{mis}) parts such that $Y_{com} = (Y_{obs}, Y_{mis})$.[9] **Figure 2** illustrates this process, where each row is an observation and each column is a composition that sums to 1. In this process, any observation with more than two missing values requires multiple imputations because there are multiple possibilities for what each of those values could be. However, the observation with only one missing value does not require multiple imputations because there is only one possible value that allows the whole observation to sum to 1. One of the three following missingness mechanisms can be used to describe the pattern and cause of missingness in a dataset[10]:

Data are missing completely at random (MCAR) when the probability of being missing is not related to the data:

$$MCAR : P(R|Y_{\text{obs}}, Y_{\text{mis}}) = P(R).$$

Data are missing at random (MAR) when the probability of missingness is related to observed data, but is not related to unobserved data:

$$MAR : P(R|Y_{\text{obs}}, Y_{\text{mis}}) = P(R|Y_{\text{obs}}).$$

Data are missing not at random (MNAR) when neither of the above cases are true:

$$MNAR : P(R|Y_{\text{obs}}, Y_{\text{mis}}) \neq P(R|Y_{\text{obs}}).$$

Currently, Multiple Imputation (MI) is a widely used and theoretically grounded method for handling incomplete data.[11] Developed by Donald B. Rubin in the 1970s, MI addresses the uncertainty present in missingness by completing the dataset multiple times, resulting in several completed datasets that can be analyzed using standard analysis methods.[3] Unlike methods that only consider complete observations, Multiple Imputation uses information from both incomplete and complete observations, leading to greater efficiency.[12]

The multiple imputation framework involves three steps. First, a set of values is imputed for each of the missing data points, resulting in multiple complete datasets. This allows uncertainty about the missing data to be considered. After imputing, the analysis of interest is conducted on each of the complete datasets. The results from each completed dataset are then pooled using Rubin's rules, leading to a single estimate.[3]

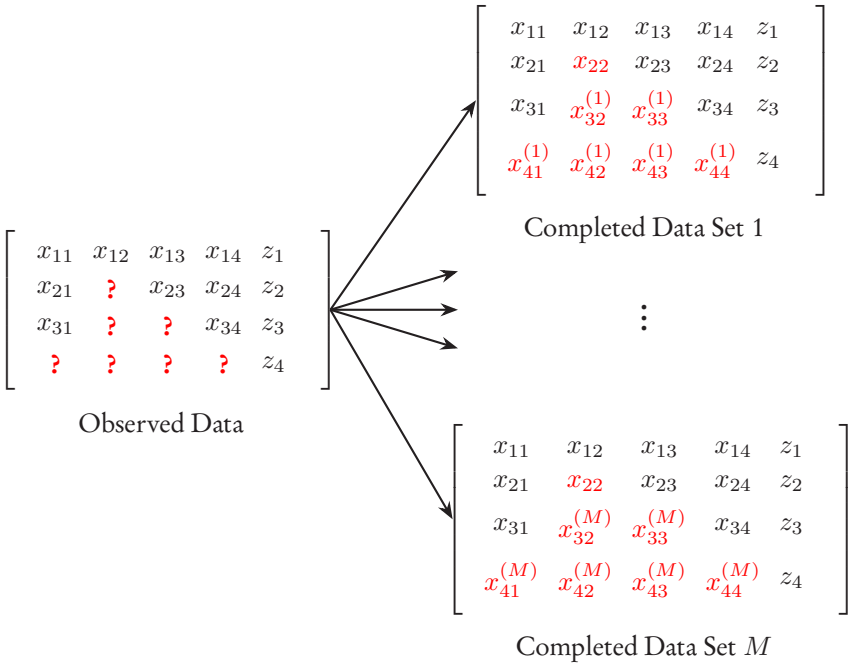

Figure 2. This diagram illustrates how the observed data (on the left) are imputed M times to create M completed data sets (on the right). The data x_{ik} for $i = 1, \ldots, 4$ and $k = 1, \ldots, 4$ are compositional data with four components observed on four study units. The data z_i are some additional completely observed variable hypothesized to be related to the compositions. Missing observations are highlighted in red text and labeled as "?" in observed data and replaced with imputations on the right as $x_{ij}^{(m)}$. Note that x_{22} does not have a completed data superscript since it is imputed only once. The value of x_{22} is known even if initially unobserved due to the geometric constraints of the sample space, i.e. the simplex, such that $x_{22} = 1 - \sum_{k \in \{1,3,4\}} x_{2k}$.

There is an abundance of literature on the imputation of conventional numerical data,[1, 9] and there are several software tools in programming languages such as R designed to work with incomplete data.[13] For example, the R package MICE (Multivariate Imputation by Chained Equations) is a popular choice for multivariate missing data.[14] The package sequentially imputes the incomplete variables to complete the dataset multiple times, in order to efficiently sample from the marginal posteriors of the missing data given the observed data, using cycles of univariate imputations for each incomplete variable.

Compositional Data

Compositional data is a subtype of multivariate numerical data where each value in the observation is a proportion or percentage, and the values must add up to a whole. While this particular behavior is similar to that of the multinomial distribution, compositional data is often made up of continuous proportions or percentages that may be dependent from observation to observation, rather than multinomial data where one must assume independent trials with a fixed number of total observations. Unlike standard numerical data, the summation constraint complicates the algebraic manipulation of compositional data. For example, if one value decreases, others must increase to maintain the sum. **Figure 3** shows responses of the first 15 subjects with complete responses in our dataset.

Compositional data is often discussed in the context of the D-part Aitchison simplex, a geometric framework for maintaining compositional data characteristics.[15] The unit simplex is the sample space for the compositional data. When all but one composition value is fixed, the final component is determined to maintain the total sum of one:

$$\text{Simplex}(S^{D-1}) = \left\{ (x_1, x_2, \ldots, x_D) \in R^D \mid x_i \geq 0, \sum_{i=1}^{D} x_i = 1 \right\}, \qquad \textbf{Equation 1.}$$

where S^{D-1} represents the $D-1$ dimensional simplex embedded in the R^D space.[6]

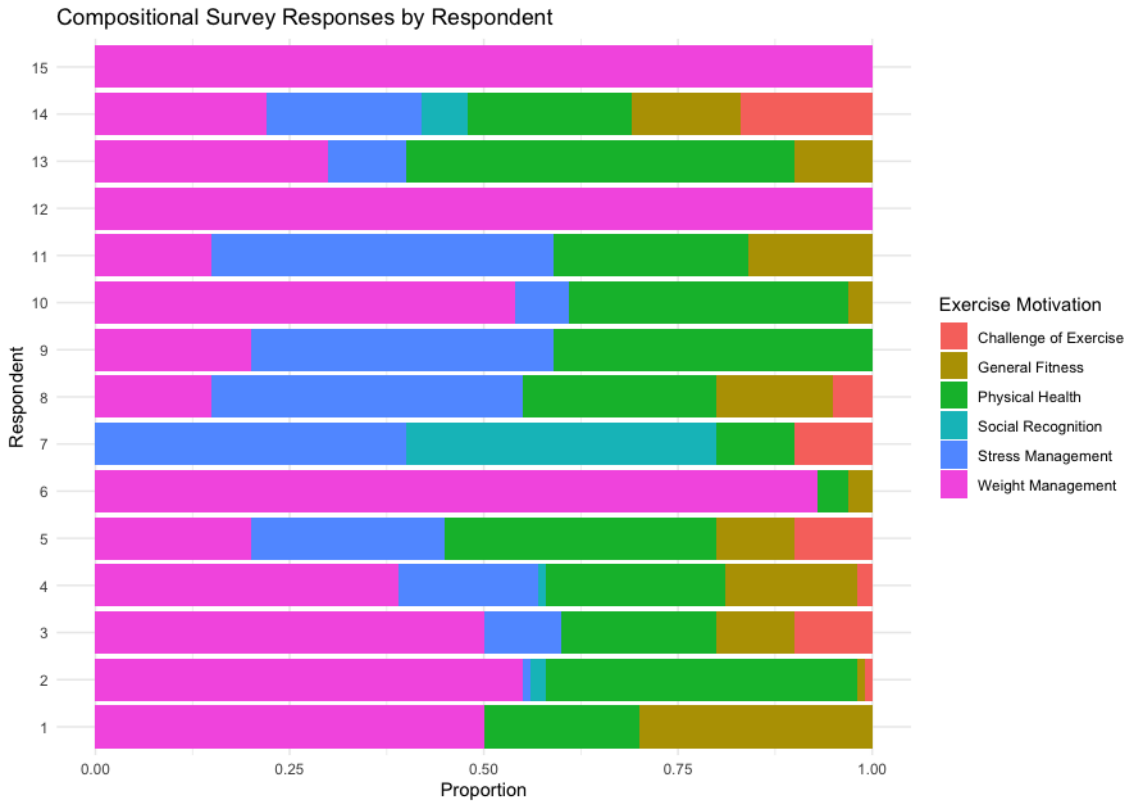

Figure 3. This bar chart shows the compositional responses to the exercise motivations survey for the first 15 respondents.

Log-Ratio transformations are a tool in compositional data analysis because they make the characteristics of compositional data easier to work with mathematically. One such characteristic is the dependency across each of the compositional parts. This dependency can result in collinearity when the compositional values are used as predictors in a model. For example, the Centered Log-Ratio (CLR) transformation is a common transformation used for compositional data because it maps original columns directly to transformed columns, making analysis and interpretation straightforward. The CLR transformation also results in a vector for each observation that sums to zero.[16] This causes collinearity to arise when fitting a linear model using all of the compositions. For this reason, we chose to work with the Isometric Log-Ratio transformation, defined as:

$$\mathrm{ILR}(x) := V^T \mathrm{clr}(x), \qquad \textbf{Equation 2.}$$

where V represents the matrix with columns that make up an orthonormal basis of the CLR-plane, V^T represents the transpose of matrix V, and $\mathrm{clr}(x)$ represents the Centered Log-Ratio transformation on a composition x defined in Equation 3.[16]

$$\mathrm{clr}(x) := \left(\log\left(\frac{x_1}{g(\mathbf{x})}\right), \log\left(\frac{x_2}{g(\mathbf{x})}\right), \ldots, \log\left(\frac{x_D}{g(\mathbf{x})}\right)\right)^T, \qquad \textbf{Equation 3.}$$

where $g(\mathbf{x})$ is the geometric mean of the components of $\mathbf{x}$,

The ILR transformation results in a vector that does not sum to a constant, allowing for a model to be computed without the issue of collinearity. The ILR data transformation allows D-part compositions to be represented as vectors unconstrained in R^{D-1}, resulting in data that are easy to analyze with most methods. The ILR transformation is useful because it allows us to circumvent issues of collinearity when building an analysis model.[16]

DATA

The motivating dataset comes from a survey of 340 participants about their motivations for exercising and their associated characteristics and demographic information. Age was the only demographic variable measured as an ordinal value. The participants' ethnicity, race, gender, income, and education levels were measured as categories or grouped into bins, with distributions as described in **Table 1**.

Factor	Group	Frequency
Age	Median	32
	Range	56 (18 – 74)
	IQR	17 (24 – 41)
Income	< $20,000	46
	$20,000 – $29,000	31
	$30,000 – $39,000	30
	$40,000 – $49,000	40
	$50,000 – $59,000	32
	$60,000 – $69,000	36
	$70,000 – $79,000	23
	$80,000 – $89,000	14
	$90,000 – $99,000	16
	> $100,000	62
Ethnicity	Not Hispanic/Latino	305
	Hispanic/Latino	23
	Prefer not to answer	10
Race	Black or African-American	48
	White	232
	Native American or Alaska Native	3
	Native Hawaiian or other Pacific Islander	27
	Asian	20
	More than one race	8
Gender Identity	Cisgender	320
	Transgender/Non-Binary	18
Gender	Male	112
	Female	210
	Non-Binary	16
Education	Less than high school	2
	High school diploma/GED	48
	Some college or technical/vocational school	114
	College graduate	98
	Some graduate school	10
	Graduate degree	66

Table 1. Frequencies of participant demographics.

The exercise motivations were measured using two different survey methods:

Survey Method 1 (EMI-2): The second volume of the Exercise Motivations Inventory (EMI-2) asks respondents to rate their agreement with questions about specific exercise motivations on a scale from 1 ("not true at all for me") to 5 ("very true for me"). These result in ordinal values, which are simpler to process, impute, and analyze. The developers of the EMI-2 questionnaire assigned the 51 questions to 14 distinct categories to summarize the responses.[17] Previous

work further narrowed these categories into six categories that broadly capture the motivations people have for exercising.

Survey Method 2 (Pie Chart Items): Survey participants were asked to indicate what percentage of their total exercise motivation can be attributed to each of six categories. The responses are required to sum to 100%, representing the individual's complete set of reasons for exercising. This method results in compositional data where the value of a response for one category must be considered relative to the others.

METHODS AND PROCEDURES

The first proposed method is the Scaling method. This method employs multiple imputation using the Predictive Mean Matching (PMM) technique to estimate the missing values at the composition component level. The PMM method involves gathering a list of candidate imputations from the closest observed responses to the predicted value for the missing response based on a Bayesian multiple linear regression model. One observation is randomly selected from the set of candidates, and the missing value is filled in using that observation.[18] During each iteration of the imputation step, we first impute on the compositional proportions, and normalize the values across each row by dividing them by the sum of the values in the row. This process ensures that the scaled values maintain relative proportions within each individual's compositional responses and sum to 1, preserving the structure of the data. Then, we perform the Isometric Log-Ratio (ILR) transformation on the completed compositions so we can use them in the analysis model.[16] This process is summarized in the top part of **Figure 4**.

The second novel method is the Isometric Log-Ratio Regression method. First, we perform an Isometric Log-Ratio transformation (ILR) on the compositional columns. The ILR transformation requires a fully observed compositional observation. To achieve this, the missing values are initially imputed with the mean value of the column. True zero values in the dataset are also replaced with a small constant to avoid undefined logarithms. The use of these mean values and small constants does not impact the forthcoming computation because these placeholder values do not remain in the data after this pre-processing step is complete. The `mice` function from the MICE R package then iterates through ten cycles of imputations to converge to the predictive distribution for the missing data. The ILR transform maps compositions from the D-part Aitchison-simplex to a $D-1$ dimensional Euclidean vector, as noted in Equation 2.[16]

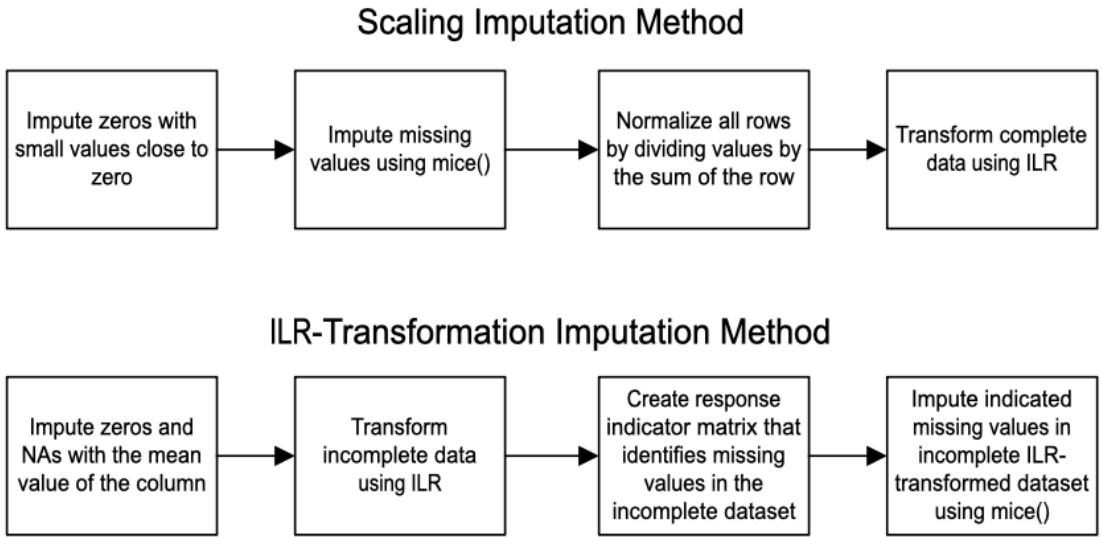

Figure 4. Flowchart detailing the steps for the Scaling and ILR-transformation imputation methods.

Then, we combine a binary response matrix to indicate the locations of missing values in the original incomplete dataset, and the demographic information with the pre-procesed ILR-transformed data. Multiple imputations are then performed

on the combined dataset using imputation by Bayesian multiple linear regression. The ILR transformed data are multivariate normal.[19] Thus, performing MICE using Bayesian linear regression allows the imputation distribution to converge to a valid joint multivariate normal distribution.[20] Finally, the function returns the imputed datasets. This process is summarized in the bottom part of **Figure 4**.

The ILR Regression method has theoretical advantages over the Scaling method, as it is based on the Isometric Log-Ratio transformation, which allows for appropriately handling compositional data by preserving the relative structure between each of the components. On the other hand, the Scaling method isn't based on any particular theoretical framework, making it more of a heuristic approach. The Scaling method may perform well empirically, as it is forcing each observation to sum to one in an intuitive way.

Simulation

We considered three methods for incomplete data analysis in comparison to analysis with the complete dataset. Each method results in a dataset that is complete and usable for analysis. The complete dataset created in the data generation step was used as the benchmark for the other methods.

For the first method, a dataset is created using the Complete Case Analysis (CCA) method[18]. When applied to a data set with compositional data, each row i with an incomplete composition, *e.g.* $(x_{i1}, ?, ?, ?, x_{i5}, x_{i6})'$ is deleted. The row-wise deletion removes the entire study unit or participant from the data set. While CCA is a simple and easy to implement ad hoc missing data analysis technique, it is often not theoretically justifiable nor an efficient use of the available data so we would not recommend its use in general. However, CCA is used in the simulations as a way to provide a minimally acceptable lower bound on the performance of other methods in the simulations.

In order to evaluate the performance of the various methods, a simulation study was performed. The simulation study and analyses for this project were all conducted using the R programming language.[13] We conducted a Monte Carlo simulation where a new dataset was generated for each iteration, and the methods under consideration were applied. This type of simulation provides an empirical evaluation of the methods' inferential performance under the considered data-generating processes.[21, 22] The steps of the simulation are as follows:

1. The simulated demographic variables are generated by sampling the empirical distributions for these variables in the original dataset.
2. The simulated compositional variables are generated by predicting ILR values using a linear model that was previously fit to the original data. Simulated data are drawn from the Aitchison distribution to generate a complete dataset with compositional and demographic values matching the structure of the original dataset.[16] The Aitchison Distribution generalizes the Dirichlet distribution and the additive log-normal distribution in order to model compositional data.
3. The simulated EMI variables are generated by predicting values using a linear model that incorporates the demographic and ILR-transformed composition data as predictors. Simulated data are drawn from the assumed univariate normal distributions from the fitted linear models.
4. Missingness is added to the simulated datasets. Four different missingness proportions ($p_{miss} = 0.1, 0.25, 0.5, 0.75$) using a MAR missingness mechanisms were applied for a combination of twelve different missingness patterns. Other MCAR and MNAR mechanisms were also evaluated.
5. The Complete Case Analysis, ILR Regression, and Scaling methods are applied to the dataset. For ILR Regression and Scaling, $M = 50$ imputations were done for each missing value.

6. For each method's completed data set, the following linear regression model is fit:

$$\begin{aligned}\text{stress}_i = \beta_0 + \sum_{k=1}^{5} \beta_k \times \text{ILR}_i + \beta_6 \times \text{age}_i \\ + \beta_7 \times \text{education}_i + \beta_8 \times \text{income}_i \\ + \beta_9 \times \text{race}_i + \beta_{10} \times \text{ethnicity}_i \\ + \beta_{11} \times \text{gender}_i + \beta_{12} \times \text{cisgender}_i + \epsilon_i.\end{aligned} \quad \textbf{Equation 4.}$$

7. The regression results are pooled by combining estimates and standard errors for β_k where $k = 0, \ldots, 12$ from the multiple imputed datasets according to Rubin's rules,[3] and the pooled summary is recorded for each of the four methods applied in the iteration.

The above steps illustrate the simulation process for one iteration. For each combination of missingness proportion and mechanism, a total of $N_{sim} = 1000$ iterations were performed.

Since MAR is the most common missing data assumption, we concentrate on this assumption. Results for MCAR and MNAR are in the appendix and discussed further in the Discussion section. In order to introduce potential bias in the CCA estimates, we use a MAR mechanism, a logistic model that induces missingness on ILR_2 that is associated with the right tail of the response variable Y, on the ILR_2 coefficient, which is defined by the equation:

$$\text{logit}(P(R = 0)) = \alpha_0 + 3Y$$

where Y represents the stress response variable, $\alpha_0 = -3\bar{Y} - \log(1/p_{miss} - 1)$ is based on the desired missingness proportion, and $\bar{Y}$ is the sample mean of the stress response. This MAR mechanism satisfies the necessary condition that the probability of missingness for the to-be amputed predictor ILR_2 has an association with response Y.[18, 22]

In the outcome regression model, the stress EMI variable is regressed on the compositions in ILR form and demographics. The stress EMI variable is representative of the relationships between the composition and the other EMI categories. The simulation results are then aggregated, including the parameter estimates and standard errors.

The summarized information is then used to calculate the average bias and coverage across each method, missingness proportion, and missingness mechanism. Bias is a measure of the error in the estimates caused by the imputation process. Measuring bias allows us to check that the imputation method does not cause the values to be consistently over- or underestimated. Using the parameters estimated from the original data set as the true values, the bias represents deviation from the ground truth. Bias is computed as follows:

$$\text{Bias}(\beta_k) = \frac{1}{N_{sim}} \sum_{i=1}^{N_{sim}} (\hat{\beta}_{k,i} - \beta_k),$$

where $\hat{\beta}_{k,i}$ is the estimate for β_k in the i-th iteration, β_k is the true parameter value, and N_{sim} is the total number of iterations.

Coverage measures the proportion of confidence intervals for each parameter that contain the true parameter value. Coverage reflects on the reliability of the methods in predicting values consistently close to the expected values. Coverage is computed using the following equation:

$$\text{Coverage} = \frac{1}{N_{sim}} \sum_{i=1}^{N_{sim}} I(\beta_k \in CI_{k,i}),$$

where N_{sim} is the total number of iterations, and $I(\beta_k \in CI_{k,i})$ is an indicator function that equals 1 if the confidence interval $CI_{k,i}$ contains the true parameter value β_k, and 0 otherwise.

Model standard error is a measure of the precision of an estimate. It measures the average standard error $\bar{SE}$ calculated for the parameter estimates. Lower model standard errors mean the model has less uncertainty in the point estimate $\hat{\beta}_k$. Model standard error is calculated as follows:

$$\bar{SE}(\hat{\beta}_k) = \frac{1}{N_{sim}} \sum_{i=1}^{N_{sim}} SE_i(\hat{\beta}_k),$$

where $\hat{\beta}_{k,i}$ is the estimated parameter with standard error $SE_i(\hat{\beta}_k)$ in the i-th iteration.

RESULTS

Simulation Results

The simulation results presented in this section are based on a MAR missingness mechanism for which our proposed imputation method and conventional multiple imputation are designed to work. Additional simulations considering a MCAR or a MNAR mechanism were performed and are presented in the appendix.

Figure 5 displays the average biases for each term across the missingness proportions within the MAR simulations. Bias is a measurement of the difference between the true value and the estimate produced by the model, indicating how often the model over- or underestimates the parameter. The figure illustrates how the ILR Regression method results in relatively low bias compared to the Scaling method. CCA also results in higher bias than the ILR regression method in most model terms, and especially in the intercept.

Figure 6 is a graph of the coverage probabilities for each method across missingness proportions. The coverage probability is the proportion of confidence intervals constructed using the data that contain the true parameter, which in this graphic is the true coefficient for each term in the model. Examining coverage probability allows us to evaluate the method's reliability because the coverage probability should match the nominal confidence interval level. From the figure, the ILR regression imputation consistently reaches the nominal level of 95% coverage at all missingness proportions, except in the ILR_2 variable where coverage is slightly decreased as the missingness proportion increases. The CCA method is unable to maintain high coverage in the ILR_2 variable with the coverage decreasing much more than the other methods. The Scaling method results in very low coverage that deviates somewhat from the expected coverage as the missingness proportion increases.

Figure 7 is a graph of the model standard error ($\bar{SE}(\hat{\beta}_k)$ for each method as the missingness proportion increases. Standard error is a measure of the uncertainty in the estimate from the fitted model, with a smaller SE indicating a more precise estimate. The figure shows that the standard errors for the ILR Regression and CCA methods increase at similar rates as the missingness proportion increases. The Scaling imputation method also results in increasing SE as the missingness proportion increases, though at a lesser degree than the CCA or ILR Regression methods. This is because as the missingness proportion increases and more observations are removed through the CCA process, the variability in the estimates increases as a result of the lower sample size.

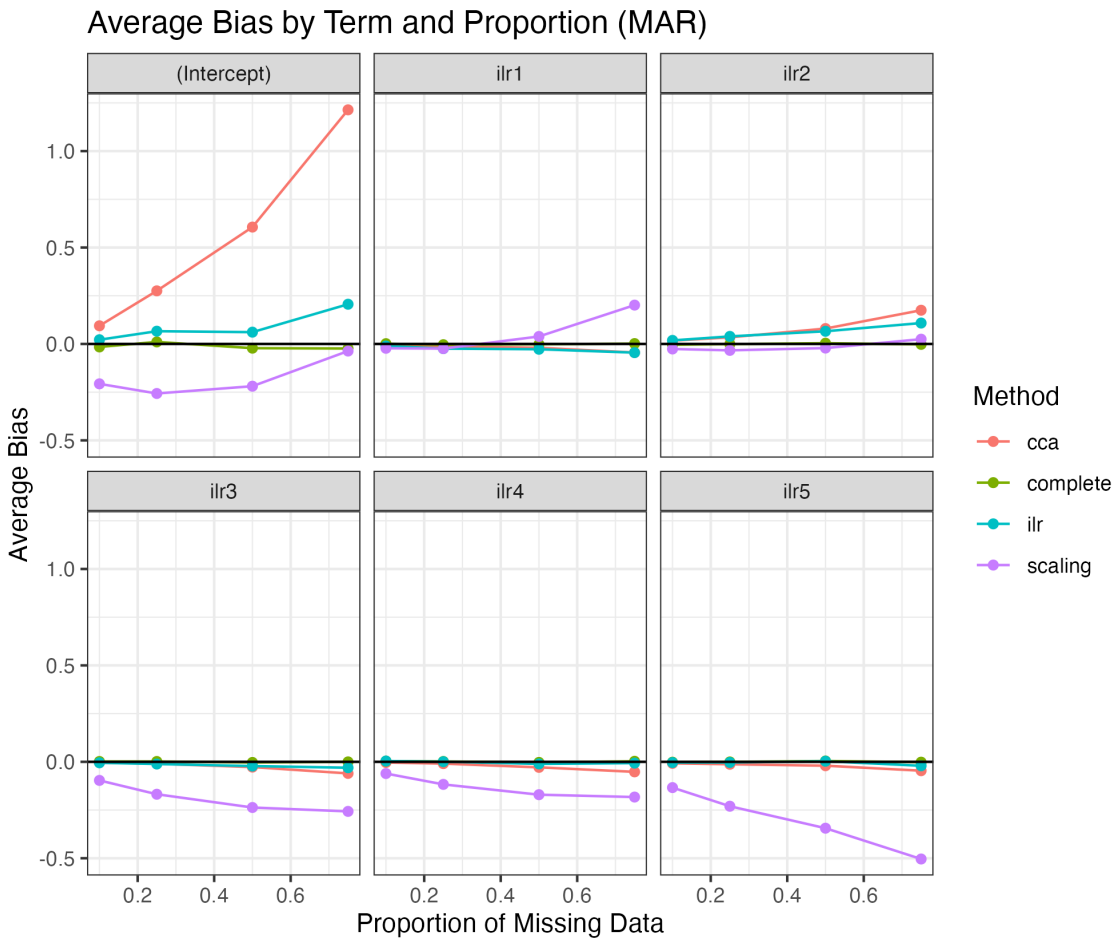

Figure 5. Graph of the average bias for each method at each missingness proportion. The averages were taken after computing the bias for each MAR simulation iteration.

Survey Data Analysis Results

One goal of the exercise motivations survey is to evaluate the relationship between the pie chart and EMI survey methods. Respondents were presented with 51 specific questions about their exercise motivations for the EMI method. The results were averaged into the six broader categories in order to match the six categories presented to the respondents for the pie chart method.

The novel ILR-transformation and scaling methods, as well as the existing CCA method, can be used to handle the missingness in the original exercise motivations dataset and draw conclusions about the relationship between the pie chart and EMI survey methods. **Figure 8** displays the missingness pattern present in the original dataset. There are three rows where each of the pie chart values are missing, including two rows where the missingness is across the entire observation. In addition to the two fully incomplete observations, one observation is missing the weight pie chart response, one is missing the social pie chart response, one is missing the challenge pie chart response, and one is missing the income demographic response.

The incomplete data were then analyzed three separate times using CCA, ILR regression imputation with MI, and scaling imputation with MI. The analysis model for each analysis was a multiple linear regression of the stress management EMI average on the predictors including the ILR transformed compositional survey responses and the respondent demographics. Stress management is used in Equation 4 as a single outcome to concisely illustrate the use of the methods, which can be readily extended to the other outcomes as well.

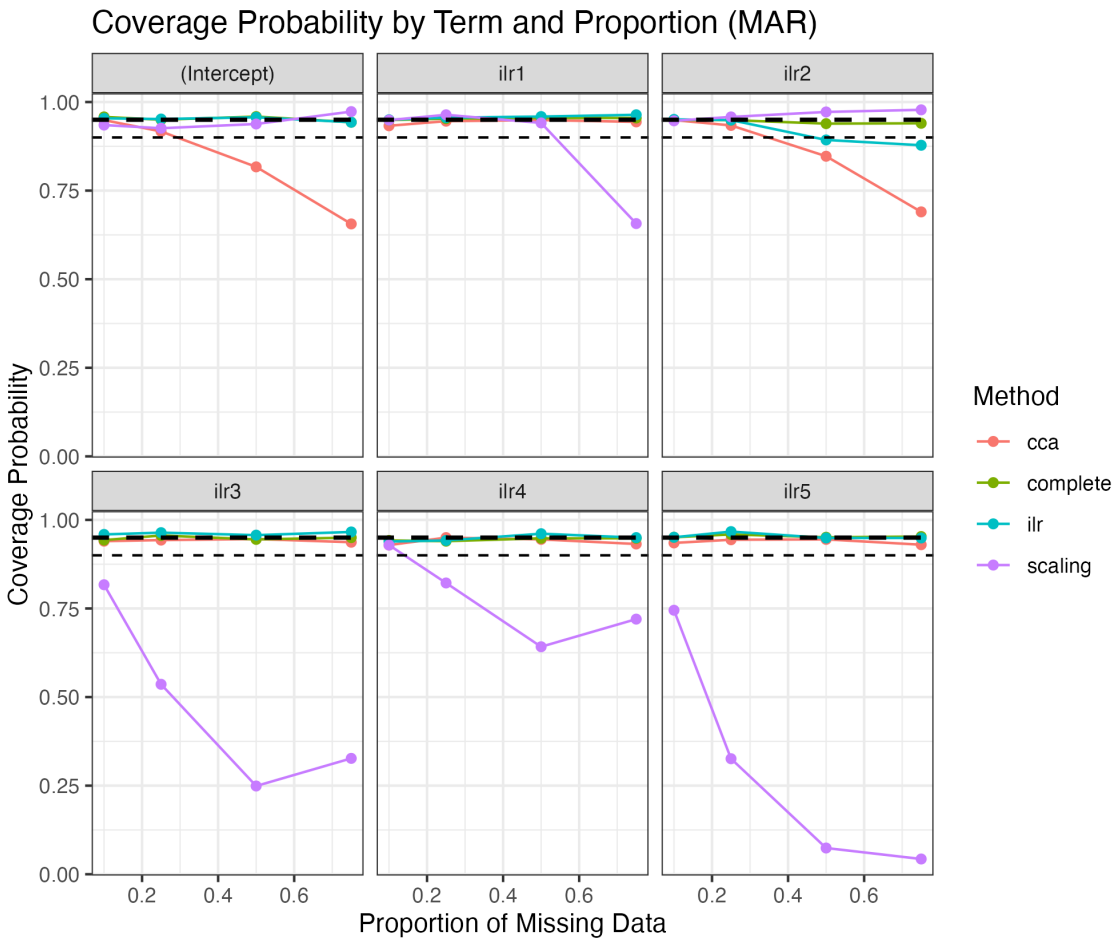

Figure 6. Graph of the coverage probability for each model term at each missingness proportion. The thinner line is at the 0.9 level, and the thicker line is at 0.95.

The estimates and their corresponding 95% confidence intervals are plotted in **Figure 9**, and **Table 2** contains the estimates, standard errors, and confidence intervals. The second ILR variable, having at most a High School diploma or GED, identifying as Female, earning between $40,000 and $49,999 annually, and identifying as Hispanic or Latino all have a significant impact on the importance of managing stress at a 95% confidence level. These significant variables are marked with an asterisk in **Table 2**.

DISCUSSION

When imputing compositional missing data, there are several considerations that need to be adequately handled to maintain the characteristics of the compositions and the legitimacy of the analysis. For example, maintaining the relationships between certain compositions is important so that imputed values are true to the structure and characteristics of the original data and respondents. Additionally, making sure that each observation sums to one is mathematically difficult to ensure. Finally, it is important to consider the mechanisms that cause the missingness, especially when it is related to experimental or social factors that are central to the experiment or study. For these reasons, it is essential that an imputation method for compositional data is well-rounded and applicable to different missingness mechanisms.

Through the simulation and following analysis, it appears that some of the evaluation metrics reflect better performance for the ILR Regression method than the Scaling method for the imputation of compositional missing data. The ILR Regression method results in consistently higher coverage probability than the Scaling method, as well as a lower magnitude of bias for all of the ILR model terms.

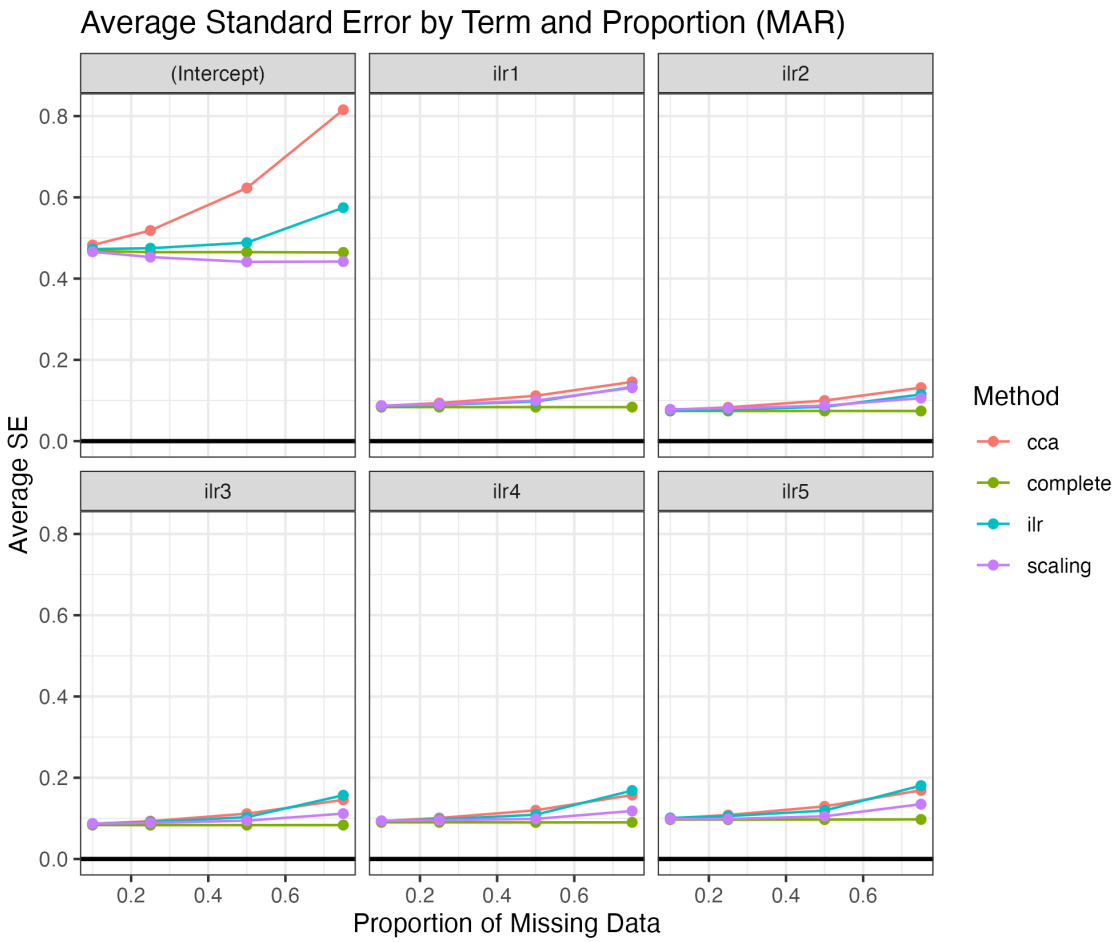

Figure 7. Graph of the standard error for each method at each missingness proportion.

To evaluate the performance of our methods under different missingness mechanisms, we also compared results across MCAR and MNAR scenarios. Results are reported graphically in the Appendix. Under MCAR, missingness is independent of both the outcome and the covariates. In contrast, the MNAR mechanism induced missingness on the second ILR variable depended directly on the values in the second ILR variable. Because of this, the MNAR results show that both Scaling and ILR Regression result in increased bias as the proportion of missingness increases, unlike the MAR and MCAR scenarios where only the Scaling method was affected. Similarly, in the MNAR case, coverage dips slightly for the second ILR variable when ILR regression is performed. These results make sense, given that MI is susceptible to increased bias in the MNAR scenario because the missingness is dependent on the values of the observed ILR values, which are a function of the pre-transformation pie-chart variables. In order to mitigate this bias when working with MNAR data, the dependency between the missingness and the observed ILR value should be captured in the imputation model.

The ILR Regression method results in consistently lower SE than the CCA method, and the magnitude of this difference increases at higher proportions of missingness. This indicates that CCA could be a reasonable missing data management method at low missingness proportions, but it results in significant uncertainty when more observations have missing data. Performing the two proposed imputation methods, alongside CCA, on the original dataset gives the opportunity to assess the performance of these methods as a sensitivity analysis when there is a very low proportion of missingness. From **Figure 9**, it appears that model estimates are somewhat similar across all approaches. However, some model terms (such as being in the $40,000-$49,999 income range or having at most a high school diploma) are significant when the dataset is imputed using the Scaling or ILR Regression methods, but insignificant when CCA is used.

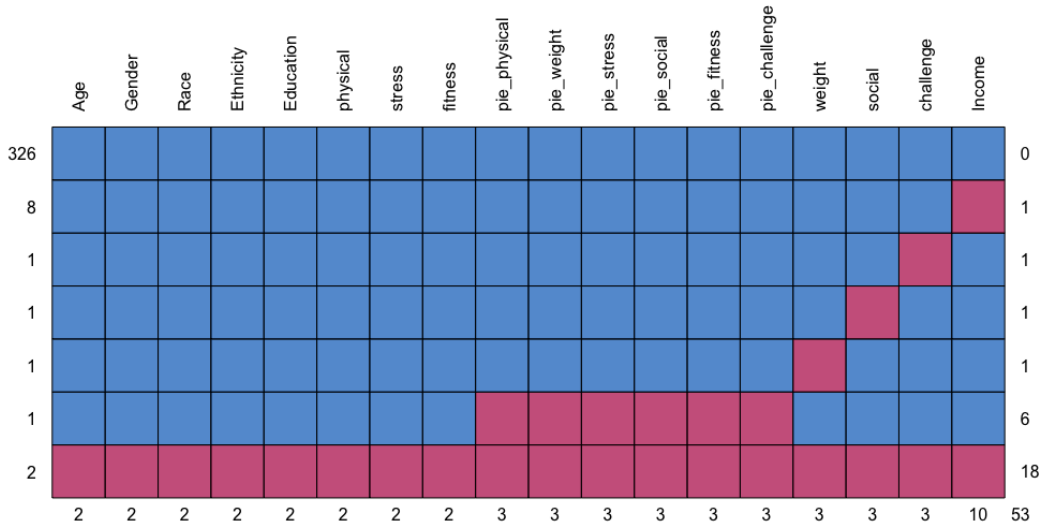

Figure 8. Missingness pattern in the original dataset.

Figure 9 also shows that CCA results in wider 95% confidence intervals around the estimates, which is a direct result of the smaller sample size associated with the higher level of missing observations. This makes a difference in the significance of some parameter estimates, and in applications where the proportion of missingness is much higher, this could make a more extreme impact on the bias of the model estimates.

CONCLUSION

When imputing incomplete compositional data, the imputation method must involve specific mathematical considerations to ensure that the imputed values maintain the characteristics of compositional data. These characteristics were considered in the development of the Scaling and ILR Regression imputation methods, and upon simulation analysis of these methods, we can see that the ILR Regression method can be used as an imputation model with multiple imputation. This method is a novel proposal for imputing missing compositional data, and it could be used in similar applications to effectively impute incomplete compositional data and use the completed datasets to generate a predictive model.

While the ILR method performs well for estimating EMI averages, interpreting the ILR variables' regression coefficients is difficult because ILR-transformed values do not have a direct relationship with the pre-ILR data. Therefore, it is not possible to use the ILR method in its current form to establish two-way relationships between the EMI averages and the compositional pie values. Future work could involve incorporating Principal Component Analysis (PCA) to find the relationships between each of the five ILR coefficients and the original columns. This would allow the impact of the ILR estimates on the EMI response variable to be measured in terms of the original compositional component categories, making the interpretation of the model more practically usable.

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Term	CCA Estimate	CCA CI	ILR Estimate	ILR CI	Scaling Estimate	Scaling CI
Intercept	2.91	[1.06, 4.75]	3.40	[1.66, 5.14]	3.28	[1.54, 5.03]
Age	0.00	[-0.01, 0.01]	0.00	[-0.01, 0.01]	0.00	[-0.01, 0.01]
Not Cisgender	0.05	[-1.59, 1.69]	0.05	[-1.59, 1.69]	0.13	[-1.52, 1.77]
Less than High School	-0.99	[-2.53, 0.55]	-1.20	[-2.75, 0.34]	-1.12	[-2.64, 0.41]
High School/GED*	-0.21	[-0.60, 0.17]	-0.43	[-0.83, -0.03]	-0.48	[-0.87, -0.08]
Some College	N/A	[N/A, N/A]	-0.21	[-0.53, 0.10]	-0.17	[-0.48, 0.14]
Some Graduate School	-0.13	[-0.87, 0.61]	-0.34	[-1.09, 0.40]	-0.30	[-1.04, 0.45]
Graduate Degree	0.28	[-0.10, 0.65]	0.06	[-0.30, 0.42]	0.12	[-0.23, 0.48]
Hispanic or Latino*	-1.17	[-1.94, -0.39]	-1.17	[-1.94, -0.39]	-1.04	[-1.81, -0.27]
Ethnicity Unknown	0.34	[-0.20, 0.88]	0.34	[-0.20, 0.88]	0.26	[-0.28, 0.79]
Female*	-0.35	[-0.62, -0.09]	-0.35	[-0.62, -0.09]	-0.39	[-0.65, -0.13]
Non-Binary	-0.21	[-1.96, 1.54]	-0.21	[-1.96, 1.54]	-0.35	[-2.09, 1.40]
< $20,000	0.08	[-0.56, 0.73]	-0.15	[-0.59, 0.30]	-0.12	[-0.57, 0.32]
$20,000-$29,999	-0.05	[-0.77, 0.66]	-0.28	[-0.79, 0.23]	-0.29	[-0.80, 0.22]
$30,000-$39,999	0.28	[-0.41, 0.97]	0.05	[-0.45, 0.54]	0.04	[-0.47, 0.55]
$40,000-$49,999*	-0.36	[-1.02, 0.30]	-0.59	[-1.04, -0.14]	-0.56	[-1.01, -0.11]
$50,000-$59,999	0.19	[-0.50, 0.87]	-0.04	[-0.52, 0.43]	-0.06	[-0.54, 0.42]
$60,000-$69,999	0.09	[-0.58, 0.77]	-0.14	[-0.59, 0.31]	-0.16	[-0.61, 0.30]
$70,000-$79,999	0.10	[-0.62, 0.82]	-0.13	[-0.67, 0.40]	-0.14	[-0.68, 0.40]
$80,000-$89,999	0.20	[-0.61, 1.00]	-0.03	[-0.67, 0.60]	0.01	[-0.62, 0.65]
$90,000-$99,999	N/A	[N/A, N/A]	-0.23	[-0.86, 0.40]	-0.17	[-0.81, 0.47]
Black/African American	N/A	[N/A, N/A]	-0.04	[-0.40, 0.31]	-0.04	[-0.39, 0.32]
Native American	0.04	[-1.32, 1.39]	-0.01	[-1.33, 1.32]	0.14	[-1.21, 1.48]
Native Hawaiian	0.00	[-0.54, 0.55]	-0.04	[-0.51, 0.43]	-0.12	[-0.58, 0.34]
Asian	0.13	[-0.54, 0.79]	0.08	[-0.51, 0.68]	0.13	[-0.42, 0.68]
More than One Race	0.36	[-0.65, 1.37]	0.31	[-0.66, 1.29]	-0.01	[-0.94, 0.92]
ilr_pie_1	-0.11	[-0.28, 0.06]	-0.11	[-0.28, 0.06]	-0.10	[-0.27, 0.07]
ilr_pie_2*	0.38	[0.23, 0.53]	0.38	[0.23, 0.53]	0.36	[0.21, 0.51]
ilr_pie_3	-0.13	[-0.32, 0.06]	-0.13	[-0.32, 0.06]	-0.13	[-0.32, 0.05]
ilr_pie_4	-0.12	[-0.30, 0.06]	-0.12	[-0.30, 0.06]	-0.12	[-0.29, 0.06]
ilr_pie_5	-0.12	[-0.33, 0.09]	-0.12	[-0.33, 0.09]	-0.11	[-0.32, 0.10]

Table 2. Table of Estimates, Standard Errors, and 95% Confidence Intervals (CI) for CCA, ILR, and Scaling Methods. The base levels for the categorical variables are: Cisgender, College Graduate, Male, Not Hispanic or Latino, earning > $100,000, and identifying as White.

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The computational work performed on this project was done with help from the Storrs High-Performance Computing cluster. We thank the UConn Storrs HPC and HPC team for providing the resources and support that contributed to these results.

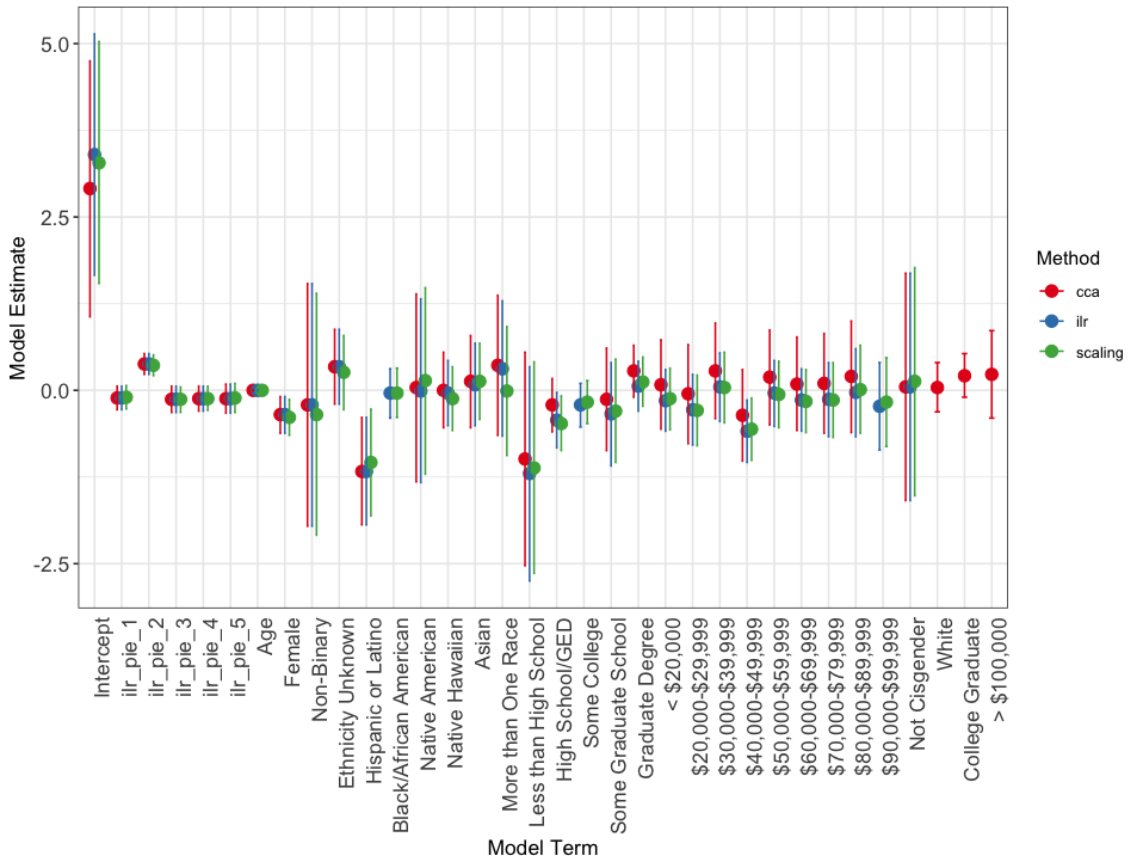

Figure 9. Dot plot with 95 percent confidence intervals representing the pooled parameter estimates, calculated after imputing the original (pre-simulation) dataset using each method.

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PRESS SUMMARY

In this paper, we present a novel method for imputing missing values in surveys involving compositional data. Unlike traditional techniques, our approach involves the use of the Isometric Log-Ratio transformation to maintain the proportional nature of the data. The method was evaluated by applying it to a dataset of responses from an exercise motivations study and the results were compared with standard methods. The ILR-based method resulted in consistent performance at different missingness proportions.

The Effect of Land Use Gradient on Adult Body Size of Bees in Eastern Tennessee

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ABSTRACT
With the intensification of agricultural practices, bee habitats are undergoing changes, impacting the nutritional quality of resources available to bee larvae and leading to variation in adult body sizes. Because larger bee species can forage at greater distances from their nests, we predicted that intraspecific body size would respond differently to agricultural land use gradient depending on bee size at the species level. Our study emphasizes the effect of a varying agricultural land use gradient on adult body sizes of bees. Our experiment took place in East Tennessee where we established twenty plots each containing 18 native plant species, at five sites of varying agricultural land-uses, ranging from 6-48% agriculture. During the summer, using an insect vacuum, we collected 11,183 insects representing 99 bee species interacting with these native plants. We then haphazardly selected adult bees from 13 species that were found at all sites to measure their body size via intertegular distance (ITD). We found that the intraspecific adult body size of larger bees, such as *Bombus impatiens*, increased along with agricultural land use in the surrounding landscape. The body size of small and medium sized bee species did not change along the agricultural land use gradient. This indicates that agricultural land use affects bee species differently. Larger bees are able to forage at greater distances from their nests and carry more provisions, which might make them more resilient to agricultural land use. Smaller bees may be less resilient because they cannot forage as far. This is critical to consider for future landscape management practices to best ensure the pollination of crops.

KEYWORDS
Pollinator Health; Wild Bees; Agriculture; Conservation; Spatial Ecology; Social Bees; Intertegular Distance; Land Use Change

INTRODUCTION

As the human population continues to grow, so does the demand for higher yielding agricultural areas, which are designed to produce the most food efficiently. However, there is a toll with this increased agricultural demand. To increase crop yield, most agricultural areas manage the land using pesticides and also decrease the amount of floral resources and wild habitat available to insects.[1,2] These changes to the land can harm beneficial insects, such as the main pollinators for these agricultural areas.[3,4] Wild insects, such as bees, provide a pollination service to 35% of the global crop production.[5] Agricultural practices can affect bee species by reducing the amount of habitat available to them during agricultural intensification. However, not all bee species are equally impacted by these changes.[6] In response to agricultural intensification, communities of some bee species are increasing, while others are declining [4].

The different responses of bees to agricultural intensification could be linked to life history traits. For example, bees can be social, living in large colonies, or solitary, living independently. Social bees have a colony structure comprised of a queen bee, female worker bees, and their brood. Social bees are successful and abundant, with large populations.[7] The larvae of social bees receive parental care until they pupate and eclose as adults to fill their new role in the colony.[8] In a social bee colony, worker bees forage daily for pollen and nectar provisions for growing young.[9]

The larvae of solitary bees depend entirely on the quality and quantity of provisions provided by the nesting female and are not tended to by workers.[10,11] A female solitary bee makes nest chambers in dirt, sand, logs, or other substrates to lay her eggs. She then packs the chambers with foraged pollen and nectar so the larvae can survive until the following season. The female bee does not return to the nest to care for her brood. Solitary bees are more diverse in terms of number of species.[11]

In both social and solitary bee species, the higher the quantity and quality of nutrients the larvae obtain, the larger and healthier they will be when they mature.[12] Thus, adult body size in bees can be associated with the availability of nutritional resources in the

area surrounding the nest or colony site.[13,14] When resources are limited or low in quality, larval provisions are smaller, resulting in smaller adult body sizes.[13] Conversely, when there are plentiful, high quality floral resources within the foraging range, larval bee growth will improve due to the abundance of nutrients, resulting in larger adult bees.[13,15] It is also possible that other attributes, such as specialization or sociality, of the bees themselves may affect their ability to collect high quality floral resources.
Land use can have a large effect on the species richness, abundance, and identity of bee species.[3,6] Habitat and landscape heterogeneity appear to support many species of pollinators. Increased agricultural habitat can limit floral diversity in bee-collected pollen provisions, which can lead to fewer bee offspring produced.[16] Some bee species can tolerate high agricultural intensities because larger adult body size allows bees to forage farther distances.[17] Overall, certain pollinators may be better adapted to urbanized areas while other pollinators are better adapted to agricultural areas.

Certain life history traits of bees can determine their response to land use.[18] The large social bumblebees, *Bombus* spp., for example, can travel further in agricultural landscapes that have fragmented patches of floral habitat and hold more provisions than their smaller, solitary bee counterparts due to their larger body size.[19] Some *Bombus* spp. can thrive in agricultural landscapes because they are resilient to habitat fragmentation.[20] Because they are generalist foragers, they may be collecting pollen both from the agricultural crops themselves and from surrounding patches of floral resources. Smaller bees, however, prefer areas with high species richness and abundance of floral display, like urban greenspaces.[21] As the intensity of monocultural farming practices increases, habitat diversity decreases.[22] Lack of habitat diversity can lead to decreases in richness and abundance in smaller bee species in high intensity land uses.[21]

Most studies focus on abundance and richness of pollinators in landscapes with high urban or agricultural land use. [6,18,22-29] Our goal was to test whether the intraspecific body size of adult bees was affected by different land uses because adult body size in bees is determined by the size and quality of the pollen provision that the larvae feed on, and agricultural land use can affect the size and quality of the pollen provision.[16,19] We therefore included a range of different land use types, from agricultural to urban. We collected bees in research plots set in five different land use types that varied in the proportion of agricultural land use at 2 kilometers from 6-48%. Our hypotheses were: 1) that larger-sized bee species would perform better (increased intraspecific body size) in agricultural areas, because their larger body size would allow them to successfully forage longer distances, 2) that smaller-sized bee species would not perform as well (decreased intraspecific body size) in more agricultural landscapes, because they would be less resilient to the fragmented and resource-poor agricultural landscapes. To test these predictions, our methods included measuring the intertegular distance (ITD) of 13 bee species collected along an agricultural land use gradient.

Material and Methods

Site selection

We used ESRI ARC GIS mapping tools to select five sites in eastern Tennessee across an agricultural land use gradient at a 2 km radius.[30] The five sites were the UTK Gardens (UTG), UTK Arboretum (UTA), UTK Organic Crops Unit (UTO), and two sites at the Plateau AgResearch Station in Crossville, TN (UTP1 and UTP2). These locations ranged in agricultural land use from 6% (UTG) to 48% (UTP1) (**Table 1**).

Site	Meters	Proportion Agriculture	Proportion Urban	Proportion Seminatural	Location Description
UTG	2000	0.06	0.60	0.23	Downtown Knoxville
UTA	2000	0.12	0.29	0.55	Forest near Oak Ridge
UTO	2000	0.32	0.15	0.49	Organic agriculture
UTP2	2000	0.38	0.05	0.55	Mixed agriculture
UTP1	2000	0.51	0.06	0.41	Cattle pasture

Table 1. The proportion of agricultural, urban, and seminatural land use around the surveyed sites. Using GIS, and the NLCD, we classified land use within a 2 km radius around each site.

Plot design

At each site, we established four common garden plots of six species from each of three plant families (Asteraceae, Fabaceae, Lamiaceae), and a mixed plot containing two species from all three families. Each plot contained the same native, perennial flower species across different sites. Each plot contained four individuals of each of the six different plant species (**Table 2**).

Asteraceae	Fabaceae	Lamiaceae	Mixed
Helianthus occidentalis (Riddell)	*Amorpha herbacea* (Walter)	*Conradina verticillata* (Jennison)	*Helianthus occidentalis*
Coreopsis lanceolata (L.)	*Senna marilandica* (L.)	*Pycnanthemum muticum* (Michx.)	*Senna marilandica*
Eurybia saxicastelli (J.N. Campbell & M. Medley)	*Baptisia albescens* (Small)	*Lycopus virginicus* (L.)	*Conradina verticillata*
Stokesia laevis (Hill)	*Lespedeza hirta* (L.)	*Physostegia leptophylla* (Small)	*Baptisia. albescens*
Helianthus hirsutus (Raf.)	*Baptisia tinctorial* (L.)	*Blephilia subnuda* (Simmers & Kral)	*Coreopsis lanceolata*
Verbesina occidentalis (Walter)	*Thermopsis villosa* (Walter)	*Collinsonia canadensis*	*Pycnanthemum muticum*

Table 2. Plant species used in the experimental research plots.

Data collection

We observed each plant species in each plot once a week between the hours of 10 am and 4 pm as they bloomed over the summer season (May-August) for five-minute intervals in 2020 and 2021. Observations occurred on clear, sunny days above 12°C. During these five-minute intervals, we collected all insects that landed on the flower using an insect vacuum. The sampled insects were then placed into -20˚C freezer for preservation and taxonomic sorting. Insects were pinned, labeled, and identified at the end of each season. Bees were identified to the species level and bee identifications were verified by Sam Droege (USGS). Specimens are vouchered at the University of Tennessee.

We haphazardly selected 25 - 134 females from 13 well-replicated (*i.e.,* at least 5 individuals present at each site) bee species from each of the five sites (between 93 – 171 females of all 13 species per site). The range is large because our lower limit to include a species was 25 females (5 at each site), but we measured as many individuals per species as possible. Some sites had many individuals of some species. The bee species included *Apis mellifera, Augochlorella aurata, Augochlorella persimilis, Augochloropsis metallica, Bombus impatiens, Ceratina calcarata, Ceratina strenua, Halictus confusus, Halictus ligatus/poeyi, Lasioglossum apocyni, Lasioglossum hitchensi, Lasioglossum imitatum*, and *Lasioglossum trigeminum.* In addition, we selected males from the two species for which males were most abundant, *Halictus ligatus/poeyi* (54 males measured) and *Halictus confusus* (47 males measured). In total, 744 individuals were selected. All species were considered eusocial, semi-social, or primitively social. No solitary bee species were included because they were not abundant enough to gain sufficient replication across all sites.

The length from the center of the left-wing base to the center of the right-wing base was measured and recorded for the results. Using LeicaS9D4DX microscope with an optical magnification of 40X, we measured the intertegular distance (ITD) in mm of each bee specimen. For smaller bee specimens, an increase of the magnification to 80X was needed. ITD has been shown to be a proxy for adult body size in bees.[24,31] For each specimen, records of the collection plot, the species, the sex, and the ITD were transcribed. We found that the bees fell into three size classes: small (< 1.75 mm), medium (1.75 mm – 3 mm), and large (> 3 mm). Our preliminary analysis showed that the species in these size categories responded differently to land use, so we aggregated the bee species into these three categories and ran separate models for each size class. Each size class was represented by more than one species.

Data analysis

Using R version 4.3.2, we used generalized linear mixed effects models (GLMMs) in the package lme4 to analyze our data.[32,33] We first built a model to see whether male and female bees (across all species) differed significantly from one another in body size. For this model, we used the ITD as the response variable, sex as the fixed effect, and the species identity as the random effect. For the purposes of this study, we were primarily interested in the effect of land use and did not expect the plot type or flower species where the bees were collected to directly affect their body size. Because there is a time lag of the effect of pollen quality on body size (i.e. the pollen determines the size of the next generation), the plant they are currently foraging on might not reflect the diet of the previous generation. We therefore used ITD as a response variable, agricultural land use at 2 km as a fixed effect, and bee species and sex as random effects. The agricultural land use at 2 km varied at the site level. We ran four separate models with this structure, one with all bees together and one for each size class of bees (small, medium, and large). Grouping bees in these size classes is commonly done in studies of the effect of land use.[34,35] We did not test the effect of agricultural land use on each species individually because of low replication.

RESULTS

In the experiment, we collected a total of 11,183 insects over two seasons. Of those, 8,205 (~74%) were bees representing 99 species. From those collected bees, 13 species had enough specimens (i.e. at least 5 at each site) to obtain sufficient replication across the five sites. For each species, we recorded and measured the average ITD ± standard deviation (SD) for both males and females (**Table 3**). Male bees were significantly smaller than female bees of the same species measured (effect size -0.13, P < 0.001, **Figure 1**).

	Female		Male	
Species	**n**	**Average ITD**	**n**	**Average ITD**
Apis mellifera	36	3.52 ± 0.13		
Augochlorella aurata	43	1.79 ± 0.17		
Augochlorella persimilis	57	1.40 ± 0.11		
Augochloropsis metallica	25	2.58 ± 0.17		
Bombus impatiens	48	4.23 ± 0.53		
Ceratina calcarata	50	1.59 ± 0.20		
Ceratina strenua	42	1.37 ± 0.12		
Halictus confusus	36	1.65 ± 0.12	47	1.50 ± 0.12
Halictus ligatus/poeyi	134	1.91 ± 0.12	54	1.79 ± 0.15
Lasioglossum apocyni	37	1.01 ± 0.09		
Lasioglossum hitchensi	49	1.19 ± 0.10		
Lasioglossum imitatum	47	0.98 ± 0.06		
Lasioglossum trigeminum	38	1.39 ± 0.10		
Grand Total	**643**	**1.87**	**101**	**1.67**

Table 3. The 13 bee species measured, including the number of each species (n) and average ITD (mm) ± standard deviation (SD), separated by sex.

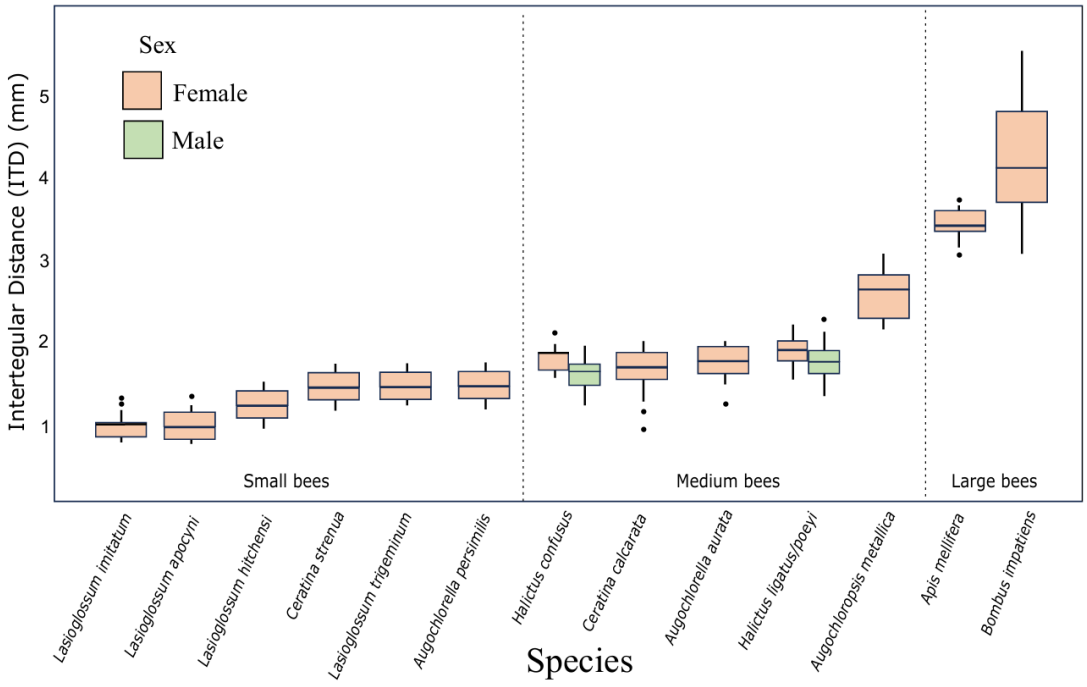

Figure 1. Box and whisker plot of the ITD of the 13 bee species measured in the three categories of bee species size (small, medium, and large), with differences between female (red) and male (green) ITD.

For the model that included all bees together, there was a significant positive relationship between agricultural land use at 2 km and bee ITD (effect size 0.11, P = 0.02, **Table 4**). However, most of the variation in body size was explained by the random

effects (species and sex, conditional $R^2 = 0.97$), while agricultural land use explained only an additional 0.03% (marginal $R^2 = 0.003$) of the variation in ITD across all bees (**Figure 2**). This was due to large differences in the responses of the species in the different size classes. Because we observed apparent differences in bees of different body sizes, we further categorized them into small, medium, and large, and repeated the analysis for each group (**Table 4**).

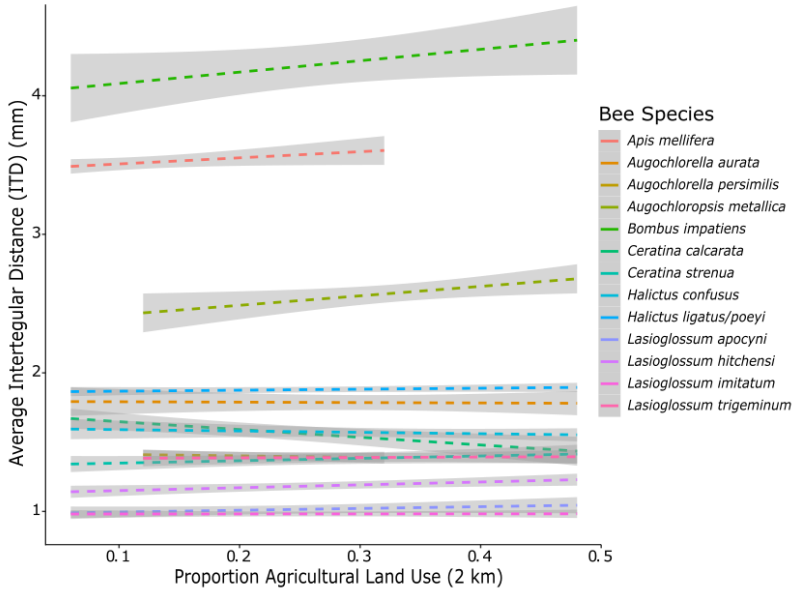

Figure 2. The relationship between ITD (mm) and agricultural land use (2 km) among the 13 bee species measured. We did not test the relationship between each species and land use, however across all species, there was not a significant effect of agricultural land use on adult body size.

Small and medium bees (i.e., bees with an ITD of less than 3 mm) were not significantly affected by agricultural land use at 2 km around the sites ($P > 0.05$, **Figure 3**). For these models, the random effects of sex and species still explained most of the variance in ITD (conditional $R^2 = 0.83$ (small), 0.90 (medium)). However, the ITD of large bees (> 3 mm ITD) increased significantly with surrounding agricultural land use (effect size = 0.77 $P = 0.02$, **Figure 3**). Agricultural land use at a 2 km radius explained 4% (marginal $R^2 = 0.04$, conditional $R^2 = 0.54$) of the variation in large bee ITD.

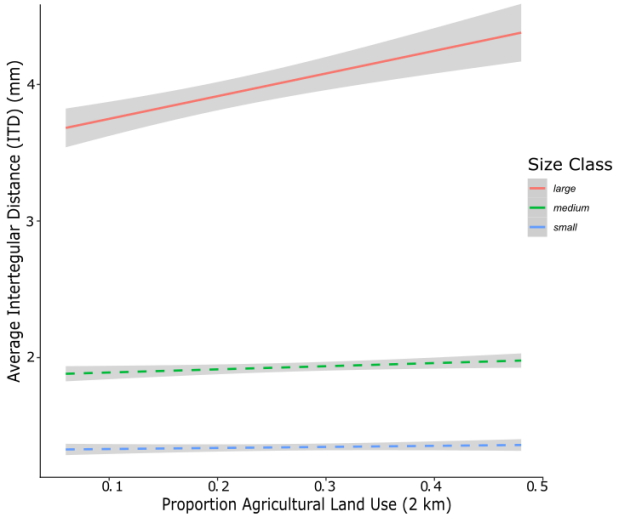

Figure 3. The relationship between agricultural land use in a 2 km radius around the site and average ITD by three size categories: small (< 1.75 mm), medium (1.75 mm – 3 mm), and large (> 3 mm). Dotted lines indicate relationships that were not significant, while solid lines indicate significant relationships.

Response	Fixed Effects	Random Effects	Observations	Effect Size	T Value	P Value	R^2m	R^2c
ITD (all bees)	Agricultural land use at 2 km	Species, Sex	744 obs, 13 Species, 2 Sexes	**0.11**	**2.3**	**0.02**	0.0003	0.97
ITD	Sex (F - M)	Species	744 obs, 13 Species	**-0.13**	**-5.49**	**<0.001**	0.002	0.97
ITD (small bees)	Agricultural land use at 2 km	Species, Sex	404 obs, 8 Species, 2 Sexes	-0.02	-0.38	0.71	<0.001	0.83
ITD (medium bees)	Agricultural land use at 2 km	Species, Sex	256 obs, 3 Species, 2 Sexes	0.11	1.85	0.06	0.001	0.9
ITD (large bees)	Agricultural land use at 2 km	Species	84 obs, 2 Species	**0.77**	**2.42**	**0.02**	0.04	0.54

Table 4. Generalized linear mixed-effects models of the relationship between ITD (mm) and agricultural land use at a 2 km radius around the site, including the fixed effects, random effects, and the number of observations. This reports effect size, T value, P value, and the marginal and conditional R^2, which explain the percentage of variation described by the fixed effects alone (R^2m) and with the random effects (R^2c).

DISCUSSION

Across diverse bee taxa, our research found agricultural land use had a significant effect on intraspecific body size on large bee species, but not small or medium bee species, in eastern Tennessee. The large bee species in our study, *Apis mellifera* and *Bombus impatiens*, had a significantly larger adult body size in sites with higher surrounding agricultural land use at a 2 km radius. Conversely, the ITD of small and medium bee species was not significantly affected by the land use gradient.

Our hypothesis was that larger bee species would perform better in agricultural environments due to their extended foraging range.[19,20,36] This hypothesis was based on the idea that larger species of bees can travel farther to get resources, and take advantage of patchy habitat in fragmented landscapes.[17] Because the size and quality of the pollen provision affects adult body size in bees, we expected that the ability of larger bees to forage farther would make them more resilient to agricultural land use.[13,15,16] These species are also generalists and can forage from many different plant species. While our findings appeared to confirm this hypothesis, it is worth noting that both larger-bodied bee species in our study are also sometimes managed for agricultural pollination.[37] Managed bees are sometimes given supplemental food, nesting habitat, and protection from diseases and parasites.[37]

Our second hypothesis that smaller bee species would perform less well (have smaller adult body sizes) in agricultural landscapes did not receive support from our data. Moreover, we did not observe an effect of agricultural land use on the body size of medium-sized bee species. This could mean that the adult body size of small and medium bee species that were present at our sites was not affected by the land use, or that our study did not capture the effects of agricultural land use on these species. For example, we only used adult body size as a measure of bee health, while other aspects of bee health, such as survival and longevity, might have been affected by land use. We also did not factor in the effect of seasonality on bee health. In addition to this, urban land use surrounding the sites might have had a differential effect on the bee species. Across our sites, agricultural and urban land use were inversely related, so urban land use may have been contributing to some of the variation in body size. Indeed, other work has shown an effect of urban land use on bee body size.[27] Future work might look at other aspects of bee health and disentangle the effects of urban *versus* agricultural land use.

Furthermore, our research might observe varying results under increased agricultural activity levels. Within our study areas, agricultural land use peaked at 48% within a 2 km radius. Adverse consequences of agricultural land use may not be discernible at these lower levels of intensity.[38] Subsequent research could explore the relationship between solitary bee adult body size and more intense agricultural land usage, for our sites were more proportional to urban land use than monocultural agriculture by being in close proximity to Knoxville, TN.

Overall, our study supported other work showing that the impact of land use on adult body size varies across species.[6,19,26,28-30,39] This suggests that managers interested in protecting the diversity of pollinators in agricultural landscapes might need to pay attention to different needs across different species. Some work has shown that native floral resource plantings *(i.e.*, flower strips) and access to natural habitat can improve the abundance and diversity of wild bees.[1,4] While the large bee species had larger body sizes in more agricultural areas in our study, that could have also been related to urban land use, or support from managers in these areas.

In addition to body size, life history traits may play a role in determining the success of bee species in highly agricultural areas. All bee species examined in our study were social or eusocial species. We chose not to incorporate true solitary bee species into our analysis due to their relative rarity compared to social bee species.[19] Consequently, we lacked sufficient replication across all sites to include solitary species in our analysis. It is plausible that the ITDs of solitary bee species could be negatively influenced by agricultural land use, given their life history characteristics.[39] However, there is a shortage of research investigating the impact of land use on solitary bee ITDs. Research that has been done has shown that solitary bees have smaller body sizes, different sex

ratios, and lower diversity and abundance in agricultural areas, suggesting land managers should consider the effects of land use on solitary bee body size as well.[4,16]

CONCLUSION

Our findings offer ecologists and land managers a means to gauge bee health and foraging range by measuring the intertegular distance of adult bees. We observed larger adult body sizes in the large, generalist, eusocial, and managed bee species *Apis mellifera* and *Bombus impatiens*. However, it is not clear whether these bees are receiving additional support from land managers. We did not observe significant effects on small and medium sized bee species. However, ITDs might be a way for land managers to identify management approaches that optimize bee health and essential pollination services. Measuring adult body size in bees could be a proxy for bee health, which is important because bees provide free pollinating services and if agricultural land use destroys bee habitat, then crop yield could decrease, with economic and ecological consequences. Given our heavy reliance on agricultural products, specifically crops that rely on bee activity, it is crucial to adjust bee management practices to match the intensifying demands of agriculture and sustain both the agricultural industry and bee populations. Because the adult body size of bees is dependent on the amount and quality of pollen they forage, we recommend that land managers provide supplemental floral resources for bees in agricultural landscapes.

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PRESS SUMMARY

As agricultural practices intensify, native habitat could be altered, affecting the native insects that reside there, in particular native bees. Our research focused on agricultural land use and the effect it had on adult bee body size. In our study, there were five sites in eastern Tennessee that ranged in agricultural land-use intensification, i.e. a city garden to a cattle pasture. We collected bees on flowers within our replicated flower beds. After collecting and identifying the specimens, we then haphazardly selected female and male adult bees within 13 different species and measured and recorded their intertegular distance, indicating the body size of the bees. Our study showed that larger bees, like bumble bees, increased in body size as agricultural land-use in the surround landscape increased. This study is important because bees provide a free pollinating service and if agricultural companies destroy bee habitat, then crop yield will decrease. It is important for land management practices to ensure the best crop yield.

Analyzing Aerosol Properties of Air Parcels Above Boone, NC, During the 2023 Summer Canadian Wildfire Season

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ABSTRACT
Air mass source regions and meteorological factors significantly influenced aerosol loading along air mass trajectories over Boone, North Carolina, between June 1, 2023, to August 31, 2023. This study examines the impact of northeast Canadian wildfires on aerosol loading, quantified by the particle light scattering coefficients at 550 nm measured at the NOAA Federated Aerosol Monitoring site at Appalachian State University (APP). Using NOAA's HYSPLIT trajectory model, hourly back trajectories originating at 500 meters above ground level at APP were analyzed over a 96-hour timespan and categorized into four aerosol loading classifications based on the aerosol light scattering coefficient at 550 nm measured at APP. All air parcel trajectories originating in eastern Canada were associated with the high and very high aerosol load classifications. Statistical analysis shows that wildfire-sourced parcels exhibit elevated temperatures and variability in solar flux. The findings establish a link between Canadian wildfire activity and increased aerosol loading in Boone, NC, emphasizing the relationships between source region, transport dynamics, and atmospheric conditions. These results provide a framework for further exploration of aerosol source regions and their broader environmental impacts.

KEYWORDS
Back-trajectory Analysis; HYSPLIT; Canadian Wildfires; Aerosols; Particle Light Scattering; Meteorology; Wildfire Impact; Air Mass Trajectories

INTRODUCTION

The Canadian fire season of 2023 was record-breaking, burning over 710,000 square miles.[1] Quebec, Northwest Territories, Alberta and British Columbia all faced unprecedented levels of tree cover loss due to wildfires in 2023 with Canadian wildfires making up 27% of the global tree cover loss for the year.[2] Significant fires included those in the Northwest Territories, where vast areas of forest and grasslands were affected. The fires were fueled by a combination of extreme heat, prolonged drought, and strong winds, which created ideal conditions for rapid fire spread and severe burning. Smoke from wildfires in Eastern Canada significantly impacted air quality across the Eastern United States. Numerous air quality alerts were issued through the summer of 2023, spanning regions from New England to the Midwest and the Southeast.

Fires in Eastern Quebec accounted for 29% of the total burned land in Canada between April and September 2023, with peak fire activity during June and July.[3] Smoke from these burns experienced transcontinental travel southeastward affecting populations downwind where the daily average $PM_{2.5}$ concentration peaked at 258.9 $\mu g/m^3$ in the northeastern United States. The World Health Organization defines $PM_{2.5}$ as particulate matter being 2.5 micrometers or less in diameter which can travel deep into the respiratory system; their air quality guideline recommends short-term exposure (24-hour) no more than 15 $\mu g/m^3$. [4] Increased exposure to $PM_{2.5}$ from wildfires affects respiratory, cardiovascular, and mental health, as well as birth outcomes. [5] In New York City, during the most intense smoke wave from June 6th to 8th, emergency department visits for asthma syndrome events increased from 181.5 per day in a reference period to 261 per day. [6] The ability to understand and predict the transport of wildfire smoke is increasingly important as the frequency of severe wildfire events has increased globally more than 2.2-fold in the last 20 years.[7]

Wildfires emit a complex mixture of gases and aerosols, primarily carbon dioxide, carbon monoxide, methane and short-lived organic aerosols and black carbon aerosols.[8] Black carbon aerosols absorb incoming solar radiation particularly well, making these emissions nearly as efficient as carbon dioxide at contributing to global warming.[9] Aerosols suspended in the atmosphere scatter incoming sunlight, reducing the amount of solar energy that reaches the surface- this is known as direct radiative forcing. Aerosol scattering also produces indirect effects, including cloud formation and alteration of meteorological processes. According to the

most recent Intergovernmental Panel on Climate Change Assessment Report (IPCC AR6, 2022)), aerosol-cloud interactions and aerosol direct radiative forcing due to scattering and absorption of sunlight by aerosols represent the largest sources of uncertainty in anthropogenic climate forcing.[10]

Located at the highest point on the Appalachian State University (APP) campus in Boone, NC (36.21°N, 81.69°W, 1080 m above sea level), the Appalachian Atmospheric Interdisciplinary Research facility (AppalAIR) is uniquely positioned to advance understanding of Southeastern U.S. (SE US) aerosols, precursor gases, and aerosol effects on regional air quality, cloud-aerosol processing, and the solar radiation budget. APP is home to the only co-located NOAA Federated Aerosol Network (NOAA FAN), NASA Aerosol Robotic Network (NASA AERONET), and NASA Micro-pulsed Lidar Network (MPLNET) sites in the U.S.. Lower tropospheric, column-averaged, and vertically-resolved aerosol optical and physical properties and concentrations are continuously measured at the site.[11–14] Refractory black carbon (BC) aerosol mass is estimated from aethalometer measurements of spectral aerosol light absorption. A meteorological station is also located on the aerosol sampling tower, located 34 m above ground level (AGL). The site is regularly exposed to air masses influenced by diverse potential aerosol sources: sulfate aerosols from power plant emissions to the west and northwest, anthropogenic organic aerosols (OA) and secondary OA (SOA) from major cities to the west, biogenic OA and SOA from the surrounding forests in the Appalachian Mountains, and BC aerosols from fossil fuel combustion and biomass burning.[16, 17]

Previous air mass transport and meteorology studies using AppalAIR data have suggested seasonal variation in aerosol sources. For example, Kelly *et al.* (2013) identified that synoptic weather patterns influenced the precipitation events in the southern Appalachian Mountain (SAM) region over a 16-month period in 2009 to 2010.[15] By combining these weather patterns with air mass back-trajectories, they determined statistical relationships between aerosol type and concentration during precipitation events measured at AppalAIR. Warm season trajectories were associated with greater aerosol loading by larger particles, consistent with oxidized, anthropogenically influenced sulfate and organic particles, whereas cool season trajectories were correlated with lower aerosol loading by particles that were thought to derive from regional biofuel burning (e.g. wood and coal stoves for residential heating).

In this study, air mass back trajectories were created hourly from June 1st to August 31st of 2023 using NOAA's HYSPLIT model. We classified each hourly trajectory using hourly-averaged aerosol light scattering coefficients measured at the NOAA FAN site at AppalAIR and further analyzed these trajectories through HYSPLIT. Our goal was to determine a relationship between origin areas of the most polluted air parcels that traveled over Boone, NC and the apportioned aerosol sourcing from Canadian wildfires. Meteorological variables from each trajectory group were statistically analyzed to uncover correlations between weather patterns and aerosol loading from these regions.

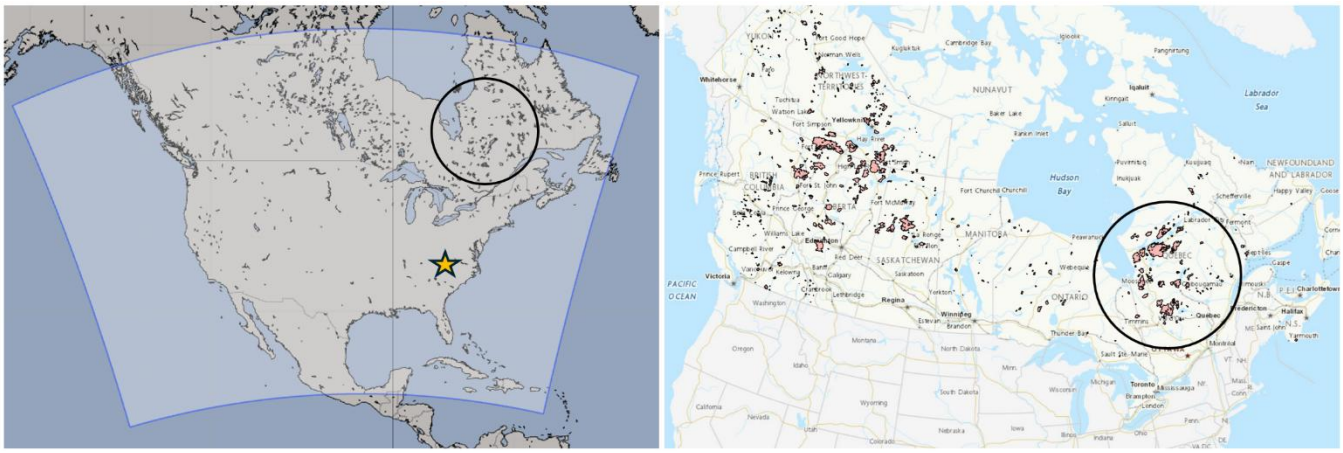

Figure 1. [LEFT] The NAM 12-km domain bounded by 152.9W, -49.4E, 12.1N, and 61.0S (from the National Centers for Environmental Information *https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00630*).[18] The AppalAIR site is indicated by the gold star. [RIGHT] Burn area is highlighted in orange on the map during June 2023 (from the Fire Information for Resource Management System (FIRMS) *https://firms.modaps.eosdis.nasa.gov/*).[19] The general region of interest from Canadian wildfires is identified with the black circle.

METHODS AND PROCEDURES

NOAA's atmospheric transport and dispersion modeling system, Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT), is widely used in simulations to describe the movement, distribution, and settling of pollutants in the atmosphere.[21] HYSPLIT has been used across diverse studies, including tracking and forecasting radioactive material, wildfire smoke, wind-blown dust, and other pollutants from natural and anthropogenic sources.[21, 22] HYSPLIT generates trajectories using the

integration method of Lagrangian modeling.[22–24] HYSPLIT back trajectories enable us to explore the source-receptor connection and the timeframes involved in long-range and local transport.[25]

HYSPLIT version 5.2 offers a variety of ways to further analyze meteorological data and back trajectories. Cluster analysis merges back trajectories into groups by minimizing the differences within an individual cluster and maximizing the differences between all clusters.[20, 27] These clusters become distinctive groups, which in recent years have been used to interpret atmospheric pollution.[26] In this study, we cluster HYSPLIT back trajectories by source region to isolate Canadian wildfire smoke and correlate the smoke with aerosol measurements made at AppalAIR for the Summer of 2023. We also employ HYSPLIT's trajectory frequency analysis which overlays a grid and displays the number of trajectories that intersect in each grid cell, normalized by the total number of trajectories.[27]

To generate back trajectories for clustering, we used the North American Mesoscale Forecast System (NAM) 12km datasets (found at *https://www.ncei.noaa.gov/metadata/geoportal/rest/metadata/item/gov.noaa.ncdc:C00630/html*) over the date range June 1, 2023, to August 31, 2023, as input to HYSPLIT. [18] Since the NAM domain is constrained to the Continental U.S. and Canada (CONUS), as shown in **Figure 1**, we limited the back trajectory time range to 96 hours; otherwise, too many back trajectories would terminate beyond the CONUS region and would be excluded from clustering and frequency analysis, especially for parcels at high altitudes subject to long-range synoptic transport. We ran HYSPLIT 96-hour back trajectories for every hour over the date range June 1, 2023, to August 31, 2023, to generate 2208 back trajectories that terminate at 500 m above ground level in Boone, NC (36.2N, 81.69W, 1080 m AGL). Note that this height is the height of the parcels at their "final" trajectory location – for example, some parcels at 500 m in Boone, NC, may have traveled well above the planetary boundary layer during transport. Even at the 96-hour back trajectory limit, roughly 7.6% of the back trajectories exceeded the NAM domain at the 500 m height and were discarded by HYSPLIT in later analysis.

Each 96-hour trajectory ending at Boone, NC, was classified into low, average, high, or very high aerosol loading bins based on hourly-averaged aerosol light scattering coefficient at 550 nm. Aerosol light scattering coefficient serves as a proxy for aerosol loading because it is directly proportional to both the aerosol number and mass concentrations, multiplied by the particle-scattering cross section and mass-scattering efficiency, respectively. Ambient air is sampled from a 34 m tower (well above the tree line) and gently heated to reduce the relative humidity (RH) of the air stream to less than 40% before entering the instruments, in accordance with standard NOAA aerosol sampling protocols.[11] Sampling at low RH decouples the confounding influences of RH and intrinsic aerosol properties on the measured scattering coefficients. The nephelometer measures light scattered in the angular range 7–170 degrees. Angular truncation effects and nephelometer light source idealities are corrected using the measured aerosol light scattering Angstrom exponent and the measured scattering coefficients are converted to their values at STP conditions (101.3 kPa, 0° Celsius) to facilitate comparisons with other sites. [29] The uncertainty in measured light scattering coefficient is approximately 10%.[28] The "low" aerosol loading classification is for hours where the measured scattering coefficient at 550 nm was less than 30 Mm^{-1}, where 1 $Mm^{-1} = 10^{-6}\ m^{-1}$. The "average" corresponds to scattering coefficients between 30 and 70 Mm^{-1}, "high" corresponds to 70 to 100 Mm^{-1}, and "very high" corresponds to a scattering coefficient greater than or equal to 100 Mm^{-1}. The classifications were determined based on 15 years of aerosol light scattering measurements at APP. [30] Trajectory clusters were generated, and frequency analysis performed at four different heights (500 m, 1500 m, 3500 m, and 5500 m) and four different aerosol load classifications (Low, Average, High, Very High) per height. In our meteorological analysis herein, we focus strictly on the 500 m heights since this corresponds to air parcels that reside within the planetary boundary layer from which the aerosol measurements were taken. We also used range-time images of normalized relative backscatter measured by the micro-pulsed lidar at APP to verify that the lower atmosphere below ~500–1000 m was well-mixed during most hours of the summer 2023 period under study, further justifying the usage of near-surface aerosol light scattering coefficients along with trajectories beginning at 500 m above the APP site.

In HYSPLIT, clustered trajectories are determined using an iterative method to minimize the total spatial variance (TSV). The TSV is a sum of the spatial variance of each cluster, where the spatial variance is the sum of the squared distances between the cluster-mean trajectory endpoint and the endpoints of that cluster's component trajectories.[23] **Figure 2** displays the percent change in TSV relative to the number of trajectory clusters for each aerosol load classification. The optimal number of clusters corresponds to the number of clusters prior to the rise in the TSV%.[27] In **Figure 2**, this criterion suggests retaining as many as eight clusters, particularly evident in the top-left and bottom-left panels for the low and high aerosol classifications, respectively. However, in all panels, the percentage change in TSV remains minimal for four clusters before rising sharply as the number of clusters decreases. Thus, we chose to limit our analysis to four clusters which is consistent with the objective percentage change criterion between 20% and 30% as recommended in the HYSPLIT documentation.[27]

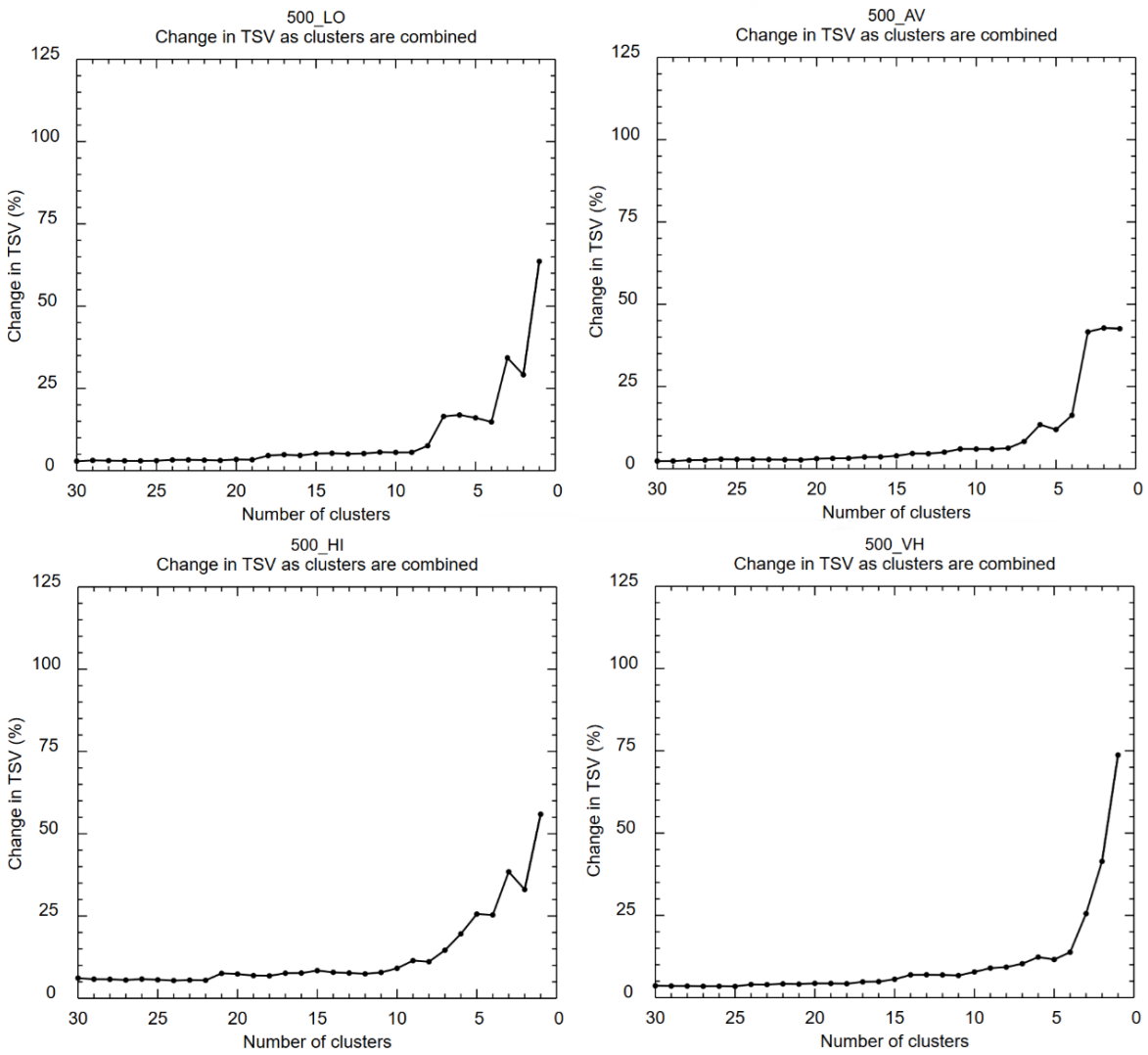

Figure 2. Percent change in TSV versus the number of clusters for each set of back trajectories at 500 m height for all aerosol load classifications. The low aerosol classification is shown in the top-left panel, the average in the top-right, the high in the bottom-left, and the very high in the bottom-right. The change in TSV informs the optimal number of clusters for our analysis. Four clusters is an appropriate choice as it marks the point where the percentage change in TSV has yet to sharply increase above 25% in all panels.

Each back-trajectory output file, *tdump*, contains meteorological variables for air parcels along the trajectory at every hour, including pressure [hPa], potential temperature [K], solar flux [$W \cdot m^{-2}$], mixing depth [m], relative humidity [%], air temperature [K], and precipitation rate [mm/hr]. For each *tdump* file, statistics such as the mean, median, maximum, and minimum were calculated for these variables. After clustering, a master database was created for each height (500 m, 1500 m, 3500 m, and 5500 m), containing the cluster number, aerosol load classification, and meteorological statistics for each aerosol observation hour. The master database enables analysis of the relationships between aerosol load and meteorology across various source regions, including those affected by the Canadian wildfires.

RESULTS AND DISCUSSION

The results of the back trajectories can be visualized in a full trajectory map. **Figure 3** shows the maps of every trajectory in each aerosol loading classification at the 500 m height. Of the 2040 valid back trajectories at the 500 m height, 744 were in the low aerosol loading classification, 891 in the average, 137 in the high, and 268 in the very high. The trajectory frequency analysis results complement the full back trajectory map by providing information on the local density and overall shape of trajectory paths, such as the curvature and divergence from the cluster mean for each category (see **Figure 4**). For the low aerosol load classification (**Figures 3a** and **4a**) and average aerosol load classification (**Figures 3b** and **4b**), the trajectories from the northeast U.S. and Eastern Canada originate east of the regions with wildfire activity and transport along the northeastern U.S.. For the high aerosol load classification category, **Figures 3c** and **4c**, the trajectories show inward spiraling from the Southwest and from the

middle region of Canada near the 100°W longitude line. For the very high aerosol load classification, **Figures 3d** and **4d**, many trajectories travel from Northeastern Canada inland, west of the Appalachian Mountain range. The high and very high share common trajectory structures that originate from or transport through the active wildfires in Canada.

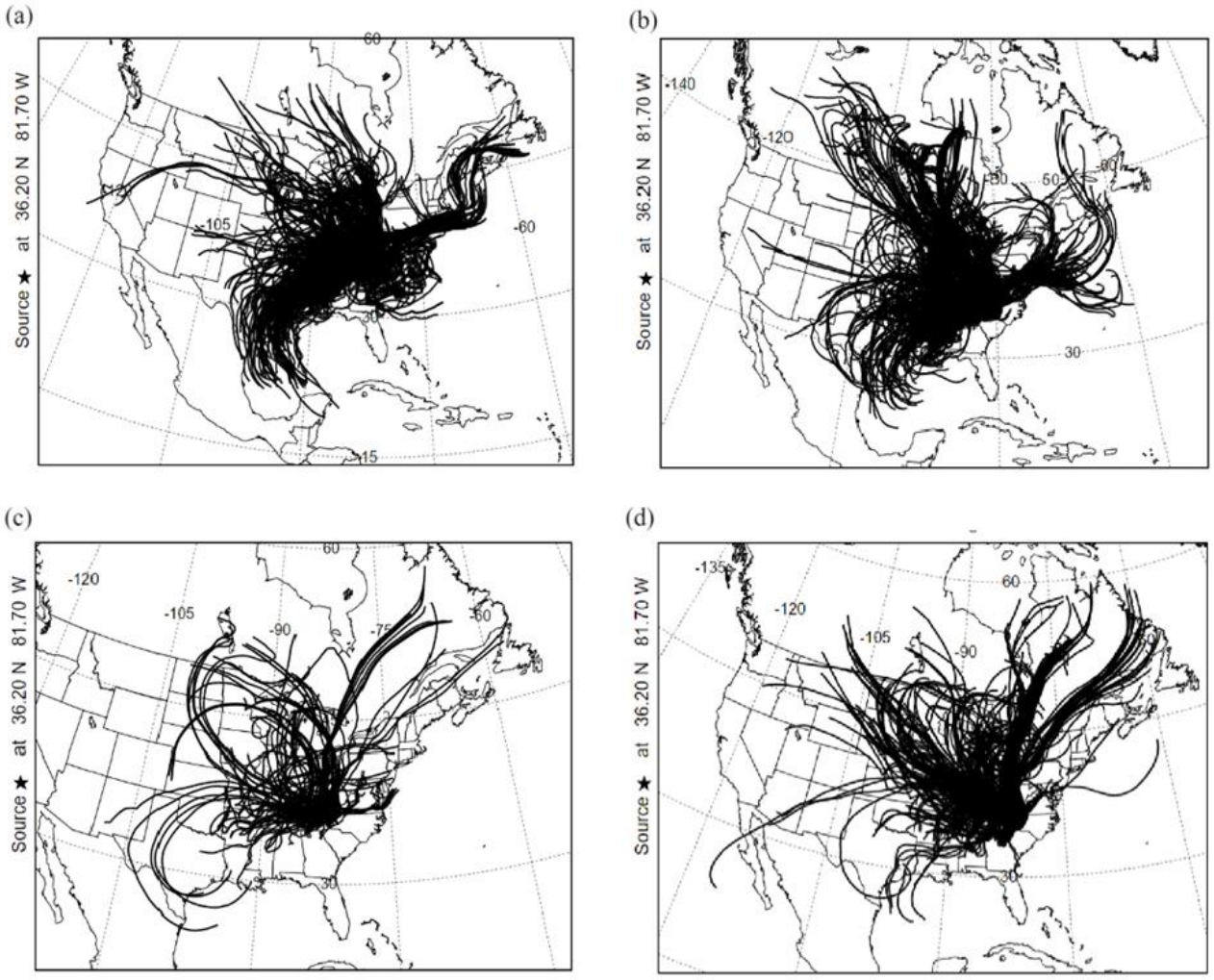

Figure 3. The HYSPLIT back trajectory map of each aerosol loading classification at 500 m. (a) low, (b) average, (c) high, (d) very high. Each line represents one 96-hour back trajectory with its starting point at 500 m above ground level in Boone, NC.

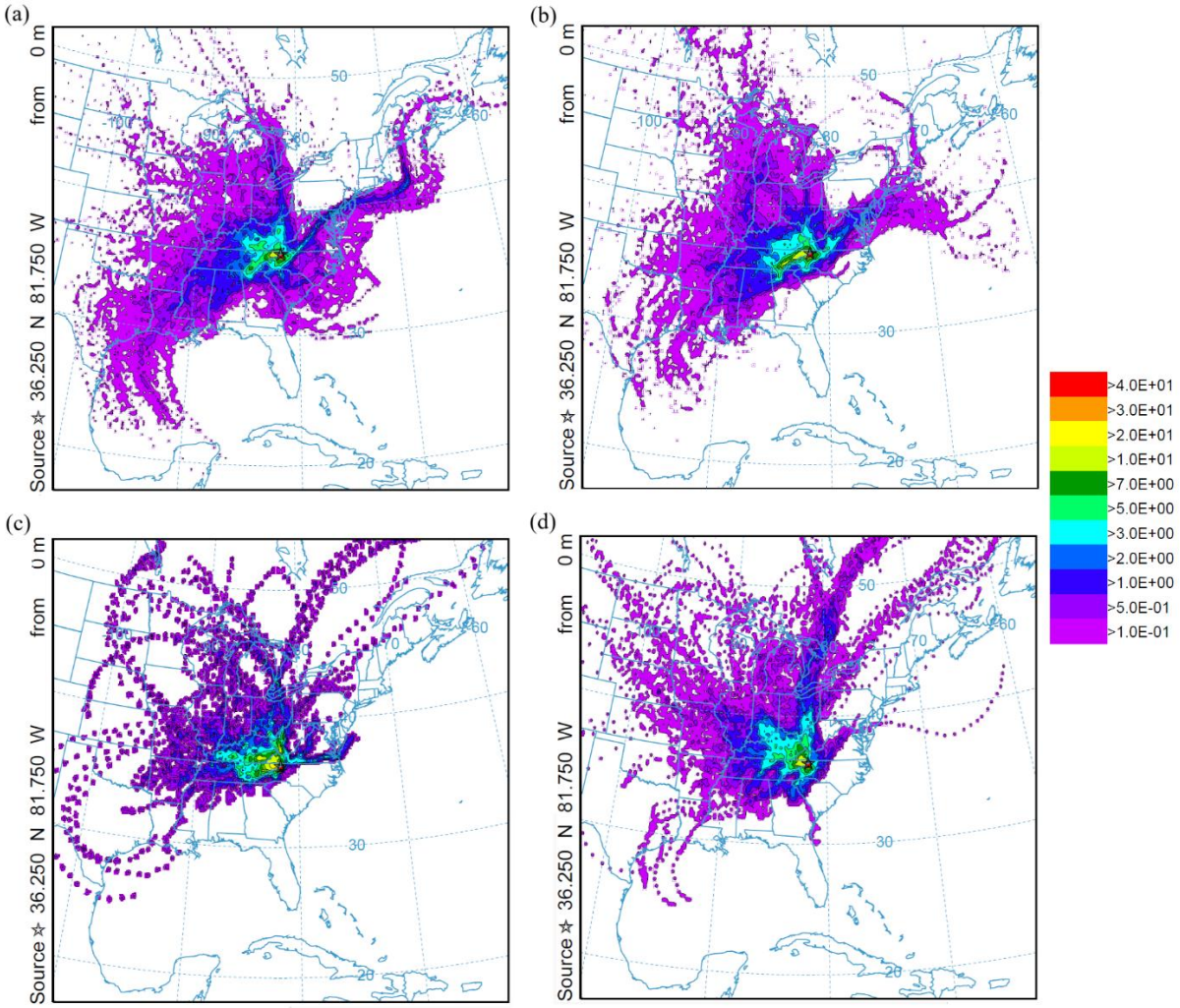

Figure 4. The results of trajectory frequency analysis at 500 m height based on aerosol classification (a) low, (b) average, (c) high, and (d) very high aerosol loading. The color-coded legend on the right indicates the number of trajectories intersecting each grid cell, normalized by the total number of trajectories for the corresponding aerosol classification.

Figure 5 shows the clustered trajectories for four clusters per aerosol load classification for the 500 m height. HYSPLIT automatically generates cluster numbers and colors for the trajectories that are not consistent between the aerosol classifications. To clarify the cluster results, we identified the clusters by source regions via regional identification acronyms (see **Table 1**). The trajectories come from five distinct regions: Eastern Maritime US (EMUS), North Central US (NCUS), South Central US (SCUS), Eastern Canada (ECAN), and the Ohio and Tennessee Valleys (OTVS) which represents the local region for the context of this study. **Table 1** also shows the number of trajectories per cluster. Trajectories unable to be clustered were discarded from the analysis by HYSPLIT, so the number of trajectories that were properly clustered is shown in the last row of **Table 1**.

Per **Figure 5**, the low and average aerosol classifications together account for 80% of all back trajectories and exhibit similar cluster trajectory paths, source regions and statistical distributions. Trajectories from the EMUS region contain no high or very high aerosol loads, while those from the SCUS region lack very high aerosol loads. In contrast, ECAN sourced clusters were classified into the high or very high aerosol load classifications throughout the study period. The local OTVS region sources more back trajectories than any other source region and contains the highest number of trajectories for all aerosol load classifications.

At the bottom of each panel in **Figure 5**, the parcel heights are plotted in meters above sea level (ASL) in which all back trajectories end in Boone, NC, at 500 m AGL, or 1470 meters ASL. The OTVS and EMUS air masses typically travel at altitudes below 1000 meters, corresponding to pressures around 898.8 hPa. [31] These lower-altitude air masses may carry aerosols or pollutants from regional emissions sources, such as vehicular or industrial emissions. In contrast, air masses originating from Canada in **Figure 5d** can reach altitudes as high as 3000 m, where the pressure drops to approximately 701.2 hPa. The higher

altitude at which these air masses travel suggests a different set of emission sources, potentially related to larger-scale agricultural activity and biomass burning. The differences in transport heights and aerosol loading between these air masses in **Figure 5** underscore the importance of considering both vertical and horizontal transport processes in the study of aerosol dynamics.

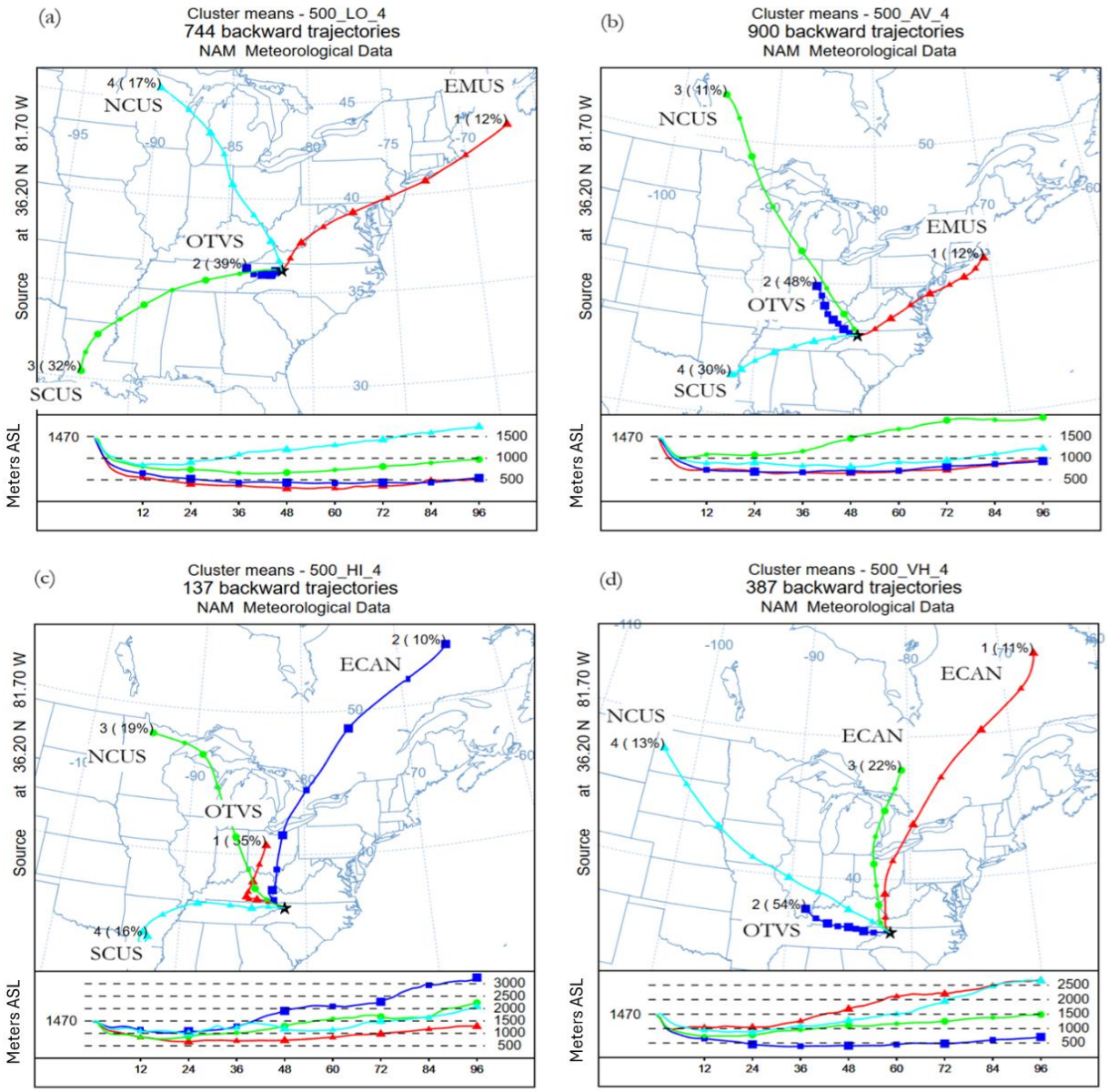

Figure 5. The results of HYSPLIT cluster analysis set to four clusters with meters ASL along the trajectory path shown below CONUS map for aerosol classification (a) low, (b) average, (c) high, and (d) very high. Each of the four cluster trajectories for low, average, high, and very high aerosol classifications are labelled with a source region ID that is detailed in **Table 1**. The total number of trajectories input for each classification is shown below the title of each panel, and the percentages next to the trajectory lines correspond to the proportion of total trajectories associated with each classification. Trajectories unable to be clustered were discarded from the analysis by HYSPLIT, so the number of trajectories that were properly clustered is shown in the last row of **Table 1**.

500 m Back-trajectories	Aerosol Load Classification							
	Low	**#**	**Average**	**#**	**High**	**#**	**Very High**	**#**
HYSPLIT Cluster – to – Source Region Identifier	C1 = EMUS C2 = OTVS C3 = SCUS C4 = NCUS	88 290 240 126	C1 = EMUS C2 = OTVS C3 = NCUS C4 = SCUS	104 429 85 273	C1 = OTVS C2 = ECAN C3 = NCUS C4 = SCUS	75 14 26 22	C1= ECAN C2 = OTVS C3 = ECAN C4 = NCUS	29 145 59 35
Number of Trajectories		744 (36%)		891 (44%)		137 (7%)		268 (13%)

Table 1. Clustered Source Region Acronyms. HYSPLIT Cluster – to – Source Region Identifier for each aerosol classification as shown in **Figure 5**. The source region identifiers are defined as: EMUS = Eastern Maritime US; NCUS = North Central US; SCUS = South Central US; OTVS = Ohio and Tennessee Valleys (local); ECAN = Eastern Canada. Analysis is performed for the 500 m final height back trajectories only. Also shown are the total number of trajectories per classification and cluster, and the total clusters and percentage of the total for each classification.

Figures 6–10 show statistical analysis of meteorological variables along the back trajectories' paths including parcel pressure [hPa], relative humidity [%] (RH), precipitation rate [mm/hr], air temperature [K], and solar flux [$W \cdot m^{-2}$]. Parcel pressures (**Figure 6**) are consistent with the clustered trajectory altitudes (**Figure 5**, bottom plots) for all source regions. The EMUS, SCUS, and OTVS exhibit the highest parcel pressures and lowest altitudes. The ECAN and NCUS exhibit the lowest pressures and highest altitudes. Early in the NCUS and ECAN trajectories, parcels are traveling above the mixing layer, subject to the higher wind speeds associated with synoptic scale transport and are spending less time in the mixing layer subject to localized influence. Outlying low pressures across all load classifications are most likely indicative of parcels being lifted to their final altitudes in Boone.

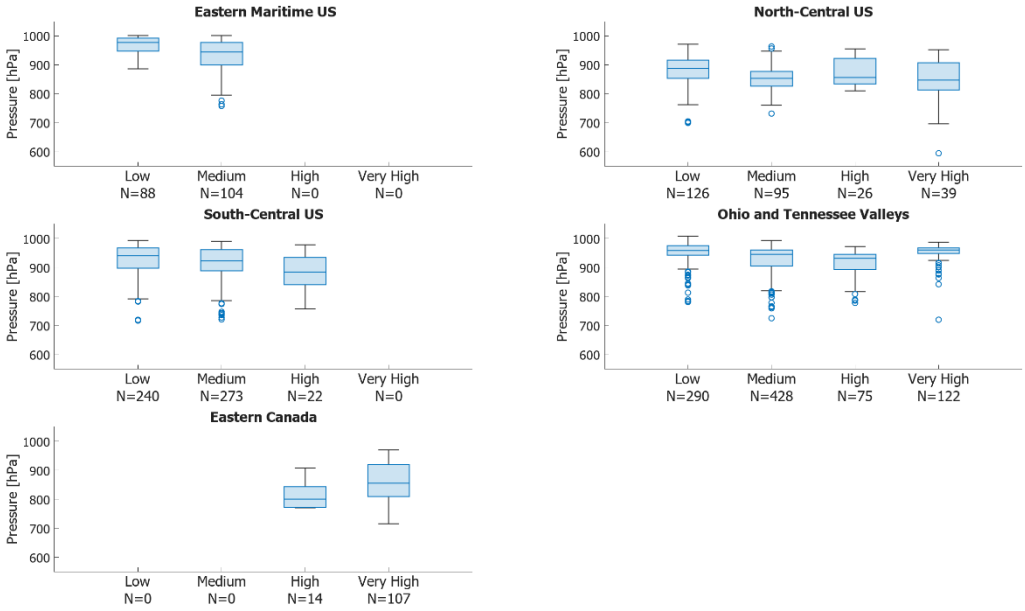

Figure 6. The results of statistical analysis of pressure [hPa] for each parcel along its back trajectory split into source region and aerosol classification boxplots.

Figure 7 is statistical analysis of solar flux values, in [$W \cdot m^{-2}$], for each clustered trajectory from each region. The median values for solar flux increase as aerosol load classification generally increases for every region. Solar flux promotes the formation of SOA within smoke, where VOCs are oxidized by sunlight and condense into new aerosol particles.[16] On the other hand, the presence of aerosols, once formed, tends to decrease solar flux due to absorption and scattering. In this study, we do not discern between the effects of diurnal aerosol processing and background wildfire smoke. At the local and regional scales (OTVS and SCUS), which are free of wildfire smoke, these results suggest that summertime aerosol loads at the local and regional scale positively correlate with solar flux, e.g. clear, sunny days lead to high aerosol loads whereas cloudy days suppress them. However, the aerosol load and solar flux for parcels from ECAN are negatively correlated, likely due to the presence of wildfire smoke and associated aerosols. The minimum value for solar flux in the very high aerosol classification is much lower for ECAN than the local and regional source regions. The large range for the quartiles and extrema in the boxplot for the ECAN very high aerosol load indicates that the very high aerosol load is only weakly dependent on the solar insolation at the source and along the trajectory paths to Boone, consistent with very high aerosol loads associated with the source wildfires.

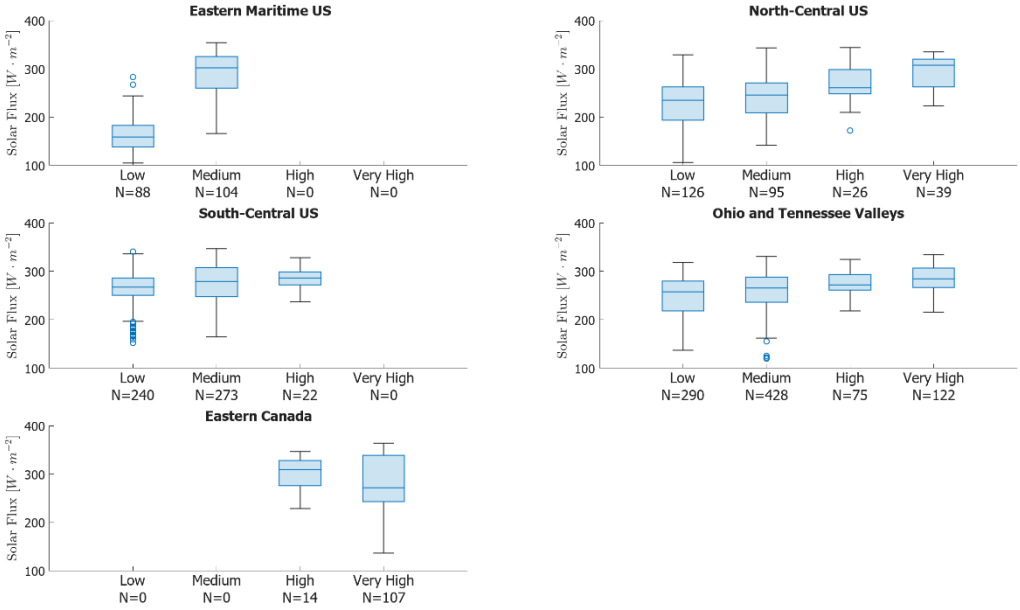

Figure 7. The results of statistical analysis of solar flux [W·m^{-2}] for each parcel along its back trajectory split into source region and aerosol classification boxplots.

Figure 8 shows boxplots for relative humidity (RH) by source region and aerosol load. For most regions, RH generally decreases as aerosol load increases except for the high and very high aerosol classifications of NCUS and ECAN. High RH generally enhances the liquid-phase reactions of trace gases and increases aerosol formation, suggesting that this analysis should show the opposite trend – that aerosol loads should increase with RH levels regardless of source region. However, competing processes such as cloud wet scavenging make it difficult to correlate RH levels with aerosol loads based on the data and analysis performed in this study with confidence.

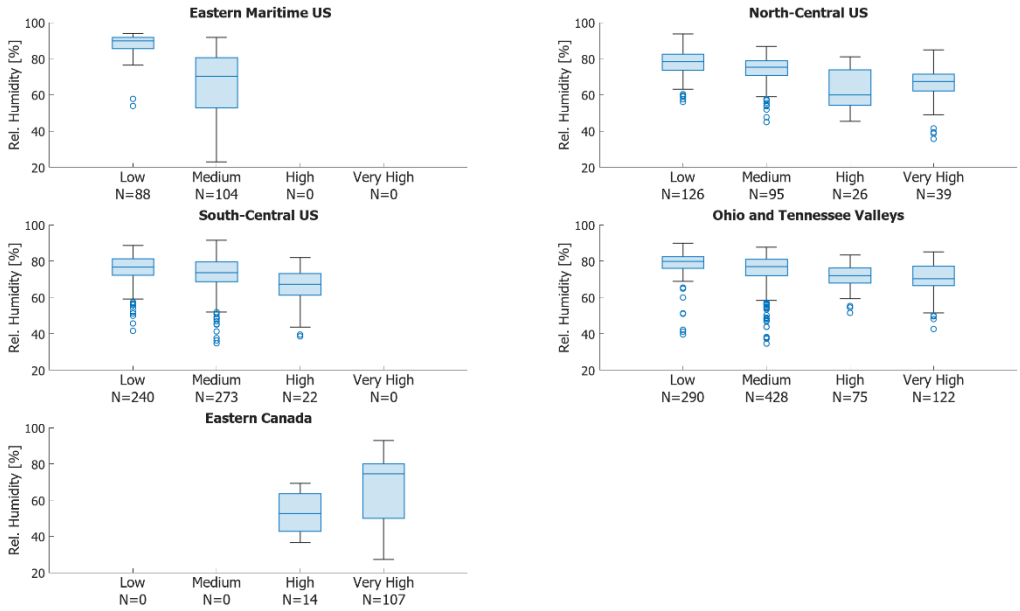

Figure 8. The results of statistical analysis of relative humidity [%] for each parcel along its back trajectory split into source region and aerosol classification boxplots.

Figures 9 and **10** show the precipitation rate [mm/hr] and air temperature [K] along the trajectory paths, respectively. As expected, aerosol loads drop with higher precipitation rate due to aerosol washout. Also as expected, air temperatures were lowest for the parcels out of ECAN, NCUS and EMUS, and highest for the SCUS and OTVS source regions. Generally, for each source region, air temperatures were roughly constant across all aerosol classifications. The exception is the unusually high air temperature for the very high out of ECAN which may correspond to the presence of sensible heat associated with aerosols released from biomass burning.

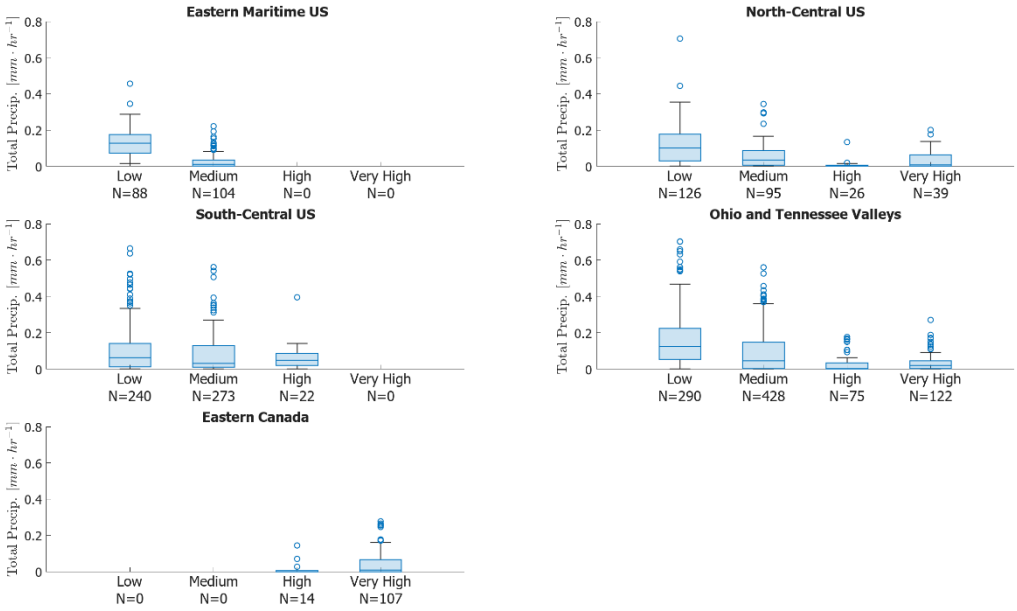

Figure 9. The results of statistical analysis of precipitation rate [mm/hr] for each parcel along its back trajectory by source region and aerosol classification.

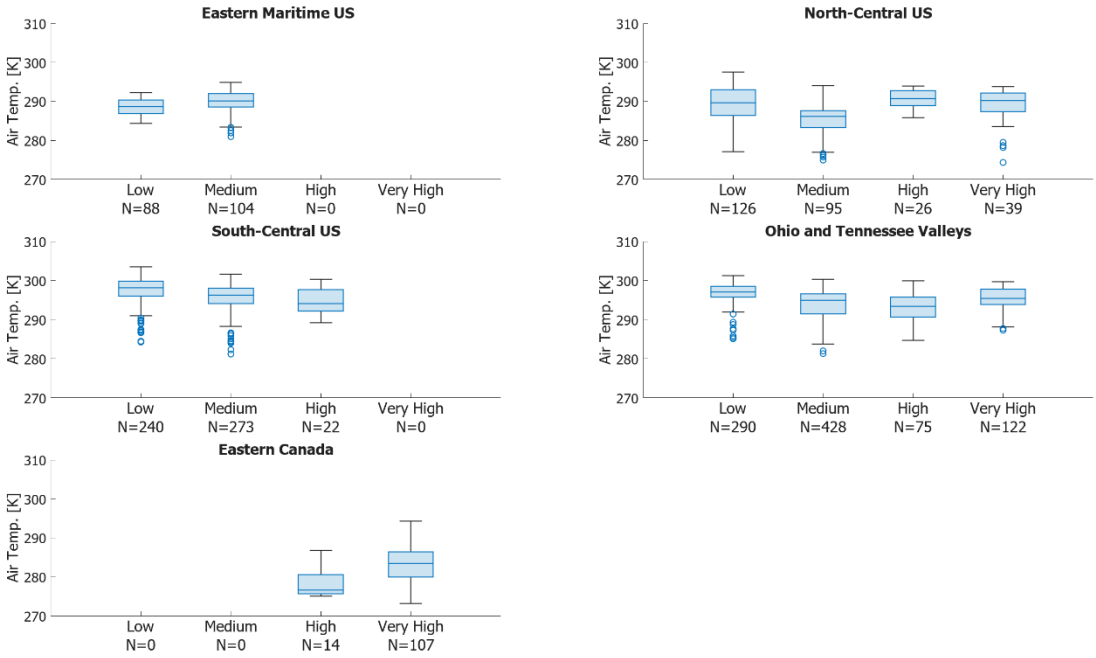

Figure 10. The results of statistical analysis of air temperature [K] for each parcel along its back trajectory split into source region and aerosol classification boxplots.

CONCLUSIONS

In this study, we sought to correlate the smoke transported from the eastern Canadian wildfires in the summer of 2023 with mid-visible aerosol light scattering measurements made at the NOAA FAN site in Boone, NC., over the same period. To simplify the analysis, we broke the aerosol light scattering measurements into aerosol loading classifications – low, medium, high, and very high – based on historical measurements made at the AppalAIR site on the Appalachian State University campus. We ran NOAA's HYSPLIT model at high temporal resolution for the summer months in 2023 and clustered the resulting back trajectories into five primary source regions, one of which is the Eastern Canada (ECAN) region from which the active wildfires emitted smoke throughout the summer season. HYSPLIT also provides meteorological information, allowing for the extraction of statistical meteorological characteristics for the parcels from each source region. The incorporation of aerosol load classification levels with HYSPLIT cluster analysis provides a comprehensive view of relationships between aerosol loading and source region as well as the meteorological conditions through which the parcels travelled.

HYSPLIT trajectory frequency and cluster analysis show distinct differences in the aerosol load classifications for each source region. Notably, the ECAN region contributes only to the high and very high aerosol loads consistent with Canadian wildfire activity during the summer of 2023. The meteorological analyses further relate to the influences of environmental factors along trajectory paths. Parcel pressure and altitude results indicate that trajectories from ECAN and NCUS travel at higher altitudes subject to synoptic scale transport. Increasing solar flux for the higher aerosol loading classifications suggest increased secondary organic aerosol formation with higher aerosol loads, though ECAN exhibits variability that aligns with wildfire contributions independent of solar insolation. Additionally, precipitation rates along each parcel trajectory follow the expected trend as precipitation effectively reduces aerosol loads, while higher air temperatures in ECAN trajectories within the very high aerosol load may reflect heat contributions from biomass burning events. Together, these findings connect source region, transport dynamics, and meteorological conditions to aerosol characteristics over Boone, NC. The contribution of Canadian wildfire emissions to high and very high aerosol classification loads underscores the role of regional wildfire activity in influencing aerosol transport and local atmospheric conditions. This analysis couples measurements of aerosol optical properties from a background SE US site with back-trajectory analysis to effectively identify aerosol source regions. Further research investigating other aerosol properties in cluster-mean trajectories would provide valuable insight into apportioned aerosol sourcing beyond the regions identified in this study. In addition, this study supports the need for synoptic and diurnal scale analysis to fully decouple traditional aerosol processing from the influences of long transport wildfire smoke.

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PRESS SUMMARY

This study investigates how smoke and aerosols from northeast Canadian wildfires during the summer of 2023 traveled to Boone, North Carolina, and influenced local air conditions. High and very high aerosol pollution levels were linked to air masses originating from wildfire-affected areas in Canada. Meteorological variables such as temperature, altitude, and sunlight interaction along air-parcel paths were tied to variations in aerosol levels. These findings emphasize the importance of understanding wildfire-driven air pollution and its long-range effects.

Hamlet in China's "Lying Flat": Resistance Through Refusal

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ABSTRACT
From the closed-door late-Qing era to the authoritative Chinese Communist Party (CCP), the Chinese government has antagonized Western literature. However, due to the Marxist foundation of the CCP, Chinese society also offers a unique proletariat literary tradition. *Hamlet* stands out as a Western text that allies the people: the hesitation, obscuration of time, and interchangeability of identity in *Hamlet* resonate with the Chinese people struggling under the extreme pressure from the authoritarian government with its grand narratives for hard work and collective success. The persisting charisma of *Hamlet* is particularly pertinent in China's "lying flat" movement, as the hard work narrative crumbles in the face of the degrading economy. The hesitation in *Hamlet* parallels the movement where people refuse to participate in the system. *Hamlet*'s cyclical revenge signals a rejection of seeking meaning under a bigger authority who forges hope, only to manipulate the people's agency repetitively. This postmodern refusal of meaning and hard work in fact provides a space for protest as the movement is already threatening the CCP's regime. Thus, this article analyzes how *Hamlet* informs both lying flat as resistance in China and how lying flat informs *Hamlet*, opening further research into the power of quitting in and beyond literature.

KEYWORDS
Hamlet; Shakespeare; Lying Flat Movement; Overwork; China; Resistance; Social Movement; Postmodernism; Literary Analysis

INTRODUCTION

It might seem surprising that a canonical Western text as *Hamlet* can still garner strong influence in the CCP-dominated contemporary China, a society where traditional values and work culture pressures converge to anonymize people's identities. *Hamlet* is a play that Harold Bloom and others have suggested virtually "invents" the human individual, making characters rather than characterizations.[1] Regardless, many *Hamlet* adaptions have emerged from the anti-individualist China—including *The Banquet* (2006) and Lin Zhaohua's theatrical production *Hamlet* (1989)—interestingly all after the establishment of the Chinese Communist Party (CCP) in 1949. More intriguingly, these adaptations in China have often placed particular emphasis on certain aspects of the *Hamlet* story: cycles of revenge with implicit and delayed actions, and disjointedness of time and identity.

Looking at the modern history of China from the late stage of the Qing dynasty to the governance of CCP today, I have found that *Hamlet* takes up unique political significance among its Chinese audience due to its many parallels with sentiments of China's "lying flat" movement that started in 2021. The movement stems from an exhaustion upon the realization that the hard work and piety dictated by CCP propaganda and traditional Chinese culture are mostly useless. In the movement, young Chinese people "lie flat": they refuse to work (or overwork), valuing their own psychological health over the betterment of the collective society thereby resisting the social structure of pressures set in place by the CCP. Their lying flat, similar to Hamlet's hesitation of action in the play, signals a break from the cycles of CCP propaganda, which can be read as analogous to the cycles of revenge in *Hamlet*. But this "break" from the system through silence or withdrawal does not simply represent a way out. Hamlet's constant self-reflection, his madness that scholars have debated about, along with a multitude of characters featuring undistinguishable identities, all coalesce into a theme about struggling to find one's identity under an assimilating social structure. His eventual revenge also reflects the inescapable shadow the system casts upon its people, the existential struggles that people face when alienated by the looming pressures of an authoritarian society.

HAMLET AND RESISTANCE IN CHINA

Chinese interpretations of *Hamlet* seem aligned with a long human history of resistance through lying flat. Human civilizations have been established based on fixed definitions of identity, usefulness, and progress so that communities and countries can work toward certain goals. Yet, when one tries to resist such pressures, such as expectation to participate in continual hard work

or to strive for societal ideals, it feels almost impossible to topple the structure. Thus, many have opted to drop out from that social structure, defining their value differently. In fact, there has been a long tradition of using "giving up" as a sign of protest against social expectations, such as the 4th-century Greek philosopher Diogenes lying in the sun, refusing to engage with the hard work as did everyone else.[2] That tradition was recently amplified by Slavoj Žižek in his repeated use of Bartelby's phrase "I prefer not to." This titular character from "Bartleby, the Scrivener: A Story of Wall Street" illustrates well the political potential of taking a stance against work by refusing to do anything.[3] It takes courage and critical thinking to resist the long-standing lifestyle wherein one is defined through one's worth (and work). As Jenny Odell writes in their book *How to Do Nothing*, "to the capitalist logic, which thrives on myopia and dissatisfaction, there may indeed be something dangerous about something as pedestrian as doing nothing: escaping laterally toward each other, we might just find that everything we wanted is already here."[2]

What is unique in China's inaction as resistance is that it is juxtaposed against the country's pervasive hard work narrative that is so closely tied into its people's identities. Additionally, in contemporary China, the short time frame in which the country has flourished economically, along with the intricate relationships between government propaganda and the people, make such resistance more difficult, but also more significant. Because the propaganda itself is collective, it places people's individual involvement into a larger narrative, making one's resistance to hard work a form of alienation from both their personal and cultural identities. That any form of resistance is censored in Chinese culture also contributes to the implicitness of this particular protest.

The timing of the widespread introduction of Shakespearean works to China, specifically *Hamlet*, could shed light on the intricate relationship between people's subjective understanding of themselves and the compulsive force of hard work ethos. After the CCP started its governance in 1949, the improved welfare and a much-needed open policy for a new government allowed more Shakespearean works to be read and adapted for theater performances. However, the people's freedom to enjoy Western artworks only constitutes an illusion of choice. The government's doctrine of Russian Marxism demanded that literary theory on Shakespearean works focus on class struggles.[4] Evidently, in the Cultural Revolution that lasted from 1966 to 1976 under Chairman Mao's leadership, the CCP aggressively destroyed everything related to foreign cultures, including books, plays, instruments, schools, etc., to strengthen his regime based on his understanding of creating a country for the proletariat.[5] Just a few years before the Cultural Revolution from 1958 to 1962, China experienced another hazard of famine resulting from "The Great Leap Forward,"[6] in which manufacturers exploited labor and forged production rates to satisfy the CCP's unrealistic production standards raised to create hopes for its communist regime. It is worthy to note that these hard work policies not only forced work upon the people but asked people to purge their minds of everything non-work-related and cast upon them a sense of responsibility in the collective manufacturing of products. During this period, one of Shakespeare's plays apparently spoke to Chinese audiences: *Hamlet*. Bian Zhilin, one of the leading Shakespeare scholars at the time, praised *Hamlet* as being written for the people instead of the ruling class because it shows Hamlet struggling for a better society.[4]

Despite various disastrous outcomes, the CCP's hard work narrative continued in cyclic ways. In 1978, the CCP implemented another policy "Reform and Opening-Up," which focused on international trade, though still framed in a way that emphasized hard work and the guidance of collective power.[7] The resulting strong economic boost lasted for about 25 years before problems started to occur. Most notably, with its economy heavily dependent on human labor, China had to loosen its one-child policy for economic progress, although the policy change did not bring about the desired effects.[8] This failed outcome also seemed to suggest that the CCP's overarching narrative was self-contradictory, leaving many wondering: if the CCP is serving the proletariat, then why does it have the privilege to change people's lives without asking their opinions?

Amid this wave of disappointed, quiet sentiment, *Hamlet* adaptations began taking space in, and reflecting, Chinese culture. Longxi Zhang, a translator and a cultural studies scholar in east-west communications, wrote that *Hamlet* still remains its strongest appeal among all Shakespearean works in China because of its focus on thinking and interpretation, following a long intellectual history in China of non-action.[9] From ancient Chinese philosophy to present, arguably the culture prefers thinking rather than speaking or acting. Confucius, one of the foundational Chinese philosophers that CCP still heavily quotes from today, teaches "think thrice before taking action."[10] Confucianism, which has been widely adopted as the orthodox rule of society by many emperors, places a strong emphasis on self-containment and etiquette to maintain the harmony of nature.[10] With the oppression stemming from the CCP as well as strict, authoritarian regimes preceding the CCP in China, it is hard for Chinese people to speak about their true thoughts. Therefore, the art of "迂回Yuhui" is valued in communication, where people manipulate "words of detour"[11] to avoid letting out their thoughts directly thereby creating more space for strategizing and reflection. The tendency to think and speak in a detour is represented in *The Banquet*, where the Empress Woman, who represents Gertrude, pulls together manipulative language instead of direct communication to help her son's revenge.[12] Also, the scene from the Chinese traditional story *Hongmen Banquet* woven into the movie illustrates a devious sword fight carried out in actual revenge hidden under the *name* (and guise) of a sword

fight performance.[12] In one of the first *Hamlet* theater adaptations in China, director Zhaohua Lin had actors change their roles constantly, making a clear identity of each character impossible.[13] "Words, words, words," (Act 2, Scene 2, line 210)[14] Hamlet exclaimed when he engaged competitively in a conversation with Polonius to try to dig out the truth of his scheme. Meant to indicate that Hamlet is reading, this line eventually turned to his comment about Polonius' scheme: every trap is set through words, lies. A clear meaning is in fact wrapped up in layers of vague words. In a more recent adaptation by the Peking Opera, "The Revenge of Prince Zidan" adopts the highly codified but ridiculous gestures of the Peking Opera genre to depict a restricted but absurd story of Hamlet.[15] It seems that *Hamlet*, as portrayed in China, focuses more on implicit narrative instead of explicit actions.

Many have already attempted to interpret *Hamlet*'s appeal to delay and uncertainty within a Western context. Hughes Glenn and Sebastian Moore state that the fluid, indeterminate actions Hamlet commits appeal to a contemporary Western society where uncertainty abounds and a clear, expected progression of stories may not be possible anymore. According to Glenn and Moore's argument, the uncertainty and fluidity of *Hamlet* that makes the story unique and represents postmodernism in current society.[16] The features of postmodernism were established by philosopher Jean-Francois Lyotard's *The Postmodern Condition* in the late 20th century. Due to the increasing commercialization of human knowledge, Lyotard writes, artificial discourse distorts truth in infinitely different ways,[17] which means that there is an increasing tendency in society to view humans' hard-earned achievements as mere commercial products exchangeable with money, diminishing the meaning of individual diligence and clear recognition of identity. A vague term, "postmodernism" has been interpreted in infinitely different ways, including a denial of objective reality, truth, science and logic as progress, a unified human nature, and language being accurate in the delivery of meaning.[18] Despite the differences in these interpretations, a shared characteristic of them is their uncertainty, a dizziness of what is true or not, whether there is, or can be, a single truth.

China's postmodernism has developed uniquely as a form of protest against Western narratives and their implicitness. Due to censorship that rejected Western ideologies in 20th-century China, and in an effort to establish the legitimacy of CCP's governance, Chinese literary critics were not able to study Western debates on postmodernism in their original and complete form.[19] Instead, they mobilized the vagueness in the definition of postmodernism and applied it to China's social and cultural context, such as reversing historical narratives that prioritize achievements of Western settlers, debunking CCP's positive narrative around economic progress, and questioning the force of individual power in the progress of collective movements.[19] As discussed above, China's contemporary history is a continuous back-and-forth between the CCP's repetitive collective propaganda and the overwhelming pressures on the people which they're supposed to take pride in. This tension between the government and the society makes people wonder who they are in the bigger narrative of hard work for the nation's progress.

China's postmodern condition can be seen reflected in the lying flat movement, after the chaos stemming from "Reform and Opening-Up," "Three Reforms," and COVID-19 pandemic with its consequent, and still dropping, yearly economic growth as well as the dehumanizing lockdown measures that stemmed from it.[19] Despite that depressing economic outlook, with CCP's determination to push for technological innovation and rejoin the world's economic competition, propaganda surrounding work flourished and workloads in China became increasingly heavy. Under such pressures, the lying flat movement started as an informal Internet meme complaining about workload, but it soon became instilled with a sense of justice and was adopted as a sign of rebellion.

Just like the postmodern condition from which it stems— that posits questions to big narratives and refuses clear definition— the lying flat movement started without a clear goal and eventually became a collective attitude, not necessarily against the government or the financial pressures, but against the fixation of a hardworking identity in the cyclical propaganda. It signals the postmodern condition of the Chinese people, realizing the distortive force of governmental, socioeconomic narratives. From the emergence of the CCP, to "The Great Leap Forward," to the COVID-19 lockdown, participants in this movement are attempting to escape the cycle of false hope from reforms through intentional aloofness. They've chosen to purposely give up as they grow disillusioned by the cyclical and seemingly futile reforms. The movement started with an article titled "Lying Flat is Justice" and quickly spread through a meme that depicts a man hopelessly lying on the couch.[21] Online discussions credit various sources for the start of the movement, including Zhuangzi's philosophy of balance and Guangdong Sanhe community's contemporary nomads.[21] There is no official organization, protests, or an explicit goal, but just the dangerous sentiments of giving up proliferating on the internet, which prompted the CCP to censor the term "lying flat."[22] However, that only encouraged more derivatives of the term: people posting pictures of themselves lying flat or advertisements of sleeping products suggesting the posture of lying flat. Instead of explicitly calling for reducing work pressures, participants gradually immunized themselves to these repetitive messages by "lying flat" – encouraging a rhetoric of turning a blind eye to work incentives. This

term has now become a popular, colloquial phrase to describe anything from the literal, phenomenological act of lying flat to an implicit protest against the entire political system.

LYING FLAT MOVEMENT IN *HAMLET*

Just as the popularity of Hamlet in contemporary Chinese culture can be seen growing alongside the past decades of discontentment and sociocultural upheaval in the country, the play itself can be read as reflecting the very movement that those conditions ultimately resulted in. In Hamlet, too, time, identity, and action seem to be as disjointed as in China's postmodern conditions. Lying flat isn't an explicitly rebellious movement; the cyclic revenge, confused time, interchangeable identity, and the inexplicable acts of madness in *Hamlet* can be read as commenting implicitly about the pressures under a strict hierarchy, the resistance against such a system.

In the arguably most famous soliloquy throughout the play, which is Hamlet's "to be or not to be speech," the prince of Denmark talks about difficulties in life that he as a royal member would never go through:

> "Th' oppressor's wrong, the proud man's contumely,
> The pangs of despised love, the law's delay,
> The insolence of office, and the spurns
> That patient merit of th'unworthy takes,
> When he himself might his quietus make
> With a bare bodkin? Who would fardels bear,
> To grunt and sweat under a weary life,
> But that the dread of something after death,
> The undiscovered country from whose bourn
> No traveler returns, puzzles the will
> And makes us rather bear those ills we have
> Than fly to others that we know not of?" (Act 3, Scene 1, 79-89)[14]

Hamlet is less likely than most of the people to have undergone oppressions and poverty, nor has he experienced death. However, in this speech, it seems that he has ceased to be Hamlet, but a common person who is archetypical of universal human struggles. Hamlet's identity becomes interchangeable with that of any other. Here I draw a parallel between Hamlet's speech and the tacit agreement among Chinese people in the lying flat movement, where people struggle with their own identity, feeling the silence of individual voices cast upon the entire humanity. In fact, Claudius may seem to Hamlet similar as to how the CCP government is perceived by the Chinese people in its collective progress narrative. He diminishes the sorrow experienced from losing Old Hamlet by changing the subject quickly from the old king's death to his new marriage during coronation, urging people into a new era hastily. "To our most valiant brother – so much for him" (Act 1, Scene 1, 96).[14] Hamlet's personal emotions here are sacrificed for the bigger narrative of the royal trajectory as Gertrude moralizes almost cruelly "all that lives must die" (Act 1, Scene 2, 74).[14] Moreover, Hamlet is constantly told by Claudius and Polonius about how to live his life. While Hamlet grieves his father, Claudius rudely interjects with "Tis unmanly grief. / It shows a will most incorrect to heaven" (Act 1, Scene 2, lines 99-100).[14] Other characters also live under the shadow of a strict, hierarchical system. Ophelia cannot even follow her romantic intuition as she is educated by Laertes and Claudius about who she should love.[14] Hamlet is the only person in the play who raises doubt against this social structure fixating on people's undistinguishable identities manipulated by hard work. As Marcellus and Horatio warn him against following the ghost, for instance, Hamlet questions, "Why, what should be the fear?" (Act 1, Scene 3, line 72)[14] manifesting his free will beyond the system. On this, Horatio comments that "he waxes desperate with imagination," (Act 1, Scene 4, line 97)[14] but imagination and thinking outside of the cycle of revenge might be the only opportunity to break through this generational tragedy.

The postmodern condition in *Hamlet* can be illustrated through the obscuration of identity throughout the play, along with many unsolved mysteries surrounding characters' identities. Shakespeare, instead of developing distinct identities for his different characters, gives them assimilated or generalized characteristics. For example, the ghost of Hamlet's father who has been guiding Hamlet in his revenge in Act 1 disappears abruptly starting from Act 2, except that he comes back briefly in Act 3, Scene 4 to remind Hamlet of his goal of revenge. The characters' identities throughout the play do not seem to be concrete. When Horatio first introduces himself, for instance, he says "A piece of him" (Act 1, Scene 1, line 24)[14] in answer to Barnardo's "Is Horatio there?" (line 1).[14] It seems that his genuine personality is not fully present and he is not sure what his entire identity is; he is only pretending to be, or only accessible to, part of him.

Some of the secondary characters in *Hamlet* are also paired up as if their experiences and emotions can be switched without implications. For example, Rosencrantz and Guildenstern always appear together to report businesses of the royal family. Almost nothing can be used to distinguish them. Hamlet's revenge storyline is also similar to that of Young Fortinbras: both are vengeful for their dead father. The two female characters, Gertrude and Ophelia, are similarly feeble, especially when it comes to Hamlet's "madness." After Hamlet insults Ophelia, instead of insulting him back or becoming angry, she laments Hamlet's change in solitude and even belittles herself to show Hamlet's previous glory:

> "O, what a noble mind is here o'erthrown! … And I, of ladies most deject and wretched, That sucked the honey of his musicked vows, Now see that noble and most sovereign reason, Like sweet bells jangled, out of time and harsh… O woe is me…" (Act 3, Scene 3, line 164-74)[14]

When Hamlet castigates Claudius' trickery against him to Gertrude, she seems to be scared and even asks what she has done wrong to herself instead of rebutting Hamlet, much like Ophelia's self-blaming. Finally, Polonius and Claudius also seem to be interchangeable. Claudius adopts Polonius' opinions without a second guess. After Hamlet mistakes Polonius for Claudius and kills him, however, Claudius continues his suppression of Hamlet despite the loss of Polonius' witty mind.

This narrative trope concerning uncertainty of identity parallels the crisis of individuality experienced in the contemporary society of China that bred the birth of the lying flat movement. Under the CCP's collectivist propaganda, people are obliged to work like human cogs within a machine without any individuality so that they can all contribute to common goals thrust upon them without any thought to their personal needs. Eventually, many within Chinese society hit a breaking point. After the pandemic lockdown, Chinese propaganda focused on rebooting the economy heavily increased, leading to people creating terms like 996 (work from 9 a.m. to 9 p.m. for six days a week) and 内卷 *neijuan* (involution) to describe everyone's same suffering under the oppressive government,[23] sacrificing their own time and assimilating themselves to a machine-like schedule. In addition, under the strict, hierarchical, and authoritarian culture of both the CCP government and traditional Chinese philosophy, people see it as a virtue to hide their true identity in exchange for politeness. Apart from relieving themselves from this pressure, people in China's lying flat movement are also seeking a form of uniqueness to distinguish themselves from the generalized working schedule that dictates life value. If postmodernism as a whole contributes to this loss of one's identity, then perhaps this quietness of identitarian expression rallies against it and can be a space for lost people to develop musings on their own, using the silence and solitary form of living as a way to figure out who they really are.

Another lying flat motif can be seen threaded throughout the plot of *Hamlet*. The cyclical nature of revenge within the play ultimately portrays such attempts as futile and impotent. These recurrent attempts at vengeance continue to morph and cause destruction in ways that mirror the relentless rounds of CCP propaganda imposed on Chinese people to cover failures in the country's economic system. The play starts with Barnardo's line "Who's there?"[14] Instead of getting a response, the question is received with an echo, "Nay, answer me."[14] This echo highlights the cyclical theme in *Hamlet* in that there is no answer, but repetitiveness resulting from people's caution, hesitation, and fear. It has become a norm in early modern revenge tragedies that when a family member dies, the rest of the family takes revenge, but a successful revenge will only lead to the death of another family member, thus starting a new round of revenge. Yet, such an obvious pattern doesn't stop the characters from pursuing revenge. It seems that people don't care about the success of the revenge but linger in the complications of performing revenge. When Hamlet mistakenly kills Polonius, for instance, the revenge plot inevitably brings Laertes into it as well. Claudius complicates the cycle of this revenge even more by irritating Laertes with "Was your father dear to you?" (Act 4, Scene 7, line 122),[14] prompting Laertes to kill Hamlet for Claudius himself. Although doing this does not facilitate Claudius's goal in trapping Hamlet, he decides to do it seemingly just to satisfy his spite against his own complicated life and to drown himself further into the cycle of revenge.

Moreover, throughout the play, the young Fortinbras' own plot has been looming behind the characters, trying to take revenge on Denmark for the death of his father. In Act 1, Scene 2, Claudius claims that he has already dismissed Fortinbras' quest for Denmark's land. Yet, toward the end of the play, Fortinbras reappears. Even more complicatedly, contradictory to his family members, Hamlet discovers the meaning of life from this enemy of his country: "This is th' impostume of much wealth and peace, that inward breaks and shows no cause without why the man dies" (Act 4, Scene 4, line 28),[14] ultimately voicing his support for electing Fortinbras.

The non-stop cycle of revenge in the play thus renders the time in the plot disjointed. Hamlet can't tell how long his father has been dead: "But two months dead – nay, not so much, not two" (Act 1, Scene 2, line 142),[14] "within a month" (line 149)[14], "a little month" (line 151).[14] In Act 1, Hamlet desires to go back to college, while Claudius acts as a fatherly figure to ask him to stay: "And we beseech you, bend you to remain here in the cheer and comfort of our eye, our chiefest courtier, cousin, and our son."[14] This makes Hamlet seem he is in his 20s. However, in Act 5, the gravedigger tells the audience that Hamlet is already 30 (Scene, 1, line 167).[14] Although Barnardo, Marcellus, and Hamlet all want to find out who the ghost is, they can't identify the time at which the ghost appears. Horatio seems to be the only one among them who at least has a general sense of time:

> Hamlet: "What hour now?"
> Horatio: "I think it lacks of twelve."
> Marcellus: "No, it is struck." (Act 1, Scene 5, lines 3-5)[14]

As noted earlier, China's lying flat movement isn't an explicitly rebellious movement, it is not a direct path to solving the problem at hand. This is similar to how Hamlet operates circuitously and doesn't immediately, directly engage revenge in any way that might be described as effective for most of the play. The effects of giving up competition in the job market, lying flat, makes a much smaller ripple than taking people's anger to the stage. It is obvious that people involved in the movement desire something more than to simply not work. Living under long-term propaganda by the CCP, people's identities have been forced into assimilation, into patriotic, subservient, working machines for the collective good of the CCP, just as how the identities of Hamlet and other characters in the play are put into vague, interchangeable, or identity seeking roles. The lying flat movement provides a chance for people to pause, allowing them a moment to not engage in the big narrative that one must contribute to social progress. A narrative that is reinforced by those in power like China's biggest company leader, Ali Baba's Jack Ma who made the following statement about working hard: "In this world, all of us want to be successful, all of us want a good life, and all of us want to be respected. I ask you, 'How can you achieve the success you want if you don't put in more effort and time than others?'"[24] But with the transition from modernity to postmodernity in China, people are rethinking the definition of success, of how their identities and lives should unfold regardless of the collective hope for the CCP's success. Yet, the answer is still not here. That's why the movement has taken its course in a way of quietness and hesitation instead of the loud protests we usually see in the history of revolution. In fact, such a silent protest may require more struggles than explicitly giving up their lives or showing their anger because it takes the patience of reflecting upon one's identity and the postmodern condition of society.

Similar to the CCP's repetitive propaganda encouraging people to work under the pressure of a degrading economy, the revenge plots in *Hamlet* have already lost their meaning and only provide an excuse for people to stalk others and become restive and oversensitive. In the restricted space of a castle, when Claudius and Polonius stalk Hamlet to figure out his madness and thus control him, Hamlet is also listening to their conversations, somehow knowing their plots against him. Hamlet once even explicitly speaks out his master knowledge of Claudius' scheme to Gertrude, "let the bloat king tempt you again to bed, and let him, for a pair of reechy kisses or paddling in your neck with his damned fingers, make you to ravel all this matter out" (Act 3, Scene, 4, lines 206-08).[14] This proves that the cyclical revenge continues due to reasons other than bringing actual success. Their revenge can be seen similar to the protesting function of the "lying flat" movement. The movement mostly spreads through participants' repetitive posting of the lying flat meme, diffusing the act of lying flat into all aspects of their lives – not only pulling out from work, but also describing all forms of rest and relaxation. Through performing the revenge, they get a better sense of who their enemies are and who they are themselves while venting out their despair, anger.

These cycles exist due to the constant pressure from the battle to win kingship and to establish the legitimacy of one's regime. Both Claudius and Gertrude try to convince Hamlet to stay instead of pursuing his personal interest at university by inculcating him to forget his father's death.[17] Ophelia is even taught how to manage her own emotions (which usually cannot be rigidly regulated) by both Polonius and Laertes.[14] Despite these lectures by people high up in the political and patriarchal hierarchy, they don't seem to be able to prevent the repeated tragedies happening in the play. Thus, characters in the play start to become confused about who they are, whether they still have agency amidst the clutter of conflicts in the story.

Struggling to find his identity and trapped in the elusive meaning of success, Hamlet often stops to ask himself of who he is, causing delays in action that may be seen as irrational, disturbing the course of progress in their revenge. Hamlet has the chance to kill Claudius in Act 3, Scene 3, but he starts to think about the happy afterlife of Claudius if he kills him at the moment and gives up doing so. In this hesitation, Hamlet's consideration doesn't entirely center around how he can torture Claudius, but on

how he hasn't been a responsible son for revenge. "I, his sole son, do this same villain send / To heaven, Why, this is hire and salary, not revenge" (line 82-84).[14] He feels that he's losing his uniqueness as an actor of revenge and is assimilated into the norms of the noble family: everything is based on an exchange of conditions, a "hire and salary," without considering one's genuine emotions. This "hire and salary" is similar to how the CCP releases one after another work-encouraging propaganda only in exchange for more loyal labor, rather than truly granting any successful prospect for individuals. When Gertrude tries to win Hamlet back by saying "Come, come, you answer with an idle tongue," (line 14) begging for the truth of Hamlet's emotions for her, Hamlet responds by "Go, go, you question with a wicked tongue" (line 15).[14] This alienation from his mother suggests Hamlet's despondent attitude toward human relationships. His revenge for his father seems to have evolved into solving the puzzle of people's ignorance of him, figuring out how he can win back his position in the noble family. The lack of explanation for the ghost and the ghost's refusal to reveal its mystery also add to the increase of delay in the play. When Horatio interrogates the identity of the ghost, saying "I charge thee, speak!" (Act 1, Scene 1, line 61)[14] it leaves. Marcellus suggests that "We do it wrong, being so majestical, to offer it the show of violence" (line 158-59).[14] The characters in the play display an indifference to orders of speed.

The elusiveness of identity can also be shown in suicidal attempts throughout the play. As Albert Camus claims in his philosophical essay "The Myth of Sisyphus," the single most important philosophical problem is suicide, judging whether one's life is worth living. To live, according to Camus, takes more courage than to die, and thus the hesitation of suicide in fact shows a struggle with the meaning of life, a struggle with finding one's identity in the course of life.[24] In Act 5, Scene 1, the gravediggers' conversation talking about Ophelia's seeming suicide also attests to Camus' argument: "For here lies the point: if I drown myself wittingly, it argues an act, and an act hath three branches – it is to act, to do, to perform" (line 11).[14] Yet, Hamlet doesn't feel at ease listening to their comfortable conversation: "That skull had a tongue in it and could sing once" (line 77-78).[14] Hamlet ponders suicide multiple times. For instance, in Act 1, Scene 2, he sighs, "O, that this too, too sullied flesh would melt, Thaw, and resolve itself into a dew."[14] But he doesn't kill himself eventually, constantly immersed in his struggles without finding a definite reason to die. Ridiculously, he was killed through an intentional murder plot (Act 5, Scene 2). Such hesitation may seem less meaningful as a symbol of struggles in life and identity than a suicide, but it is exactly such pauses in one's course of action that signals one's loss of hope in life.

Nevertheless, the delay of action and disjointment of time and identity are not only manifest through silence. In the play, the characters' lost track of time and identity can also be seen in moments of outburst. When Hamlet finally decides to fulfill his revenge plan, his words of determination still signal a sense of compulsion, unwillingness: "Sir, in my heart there was a kind of fighting / That would not let me sleep" (Act 5, Scene 2, lines 4-5).[14] This scene, despite being a successful portrayal of Hamlet's revenge, is utterly bitter. His revenge wrongfully led to Gertrude's suicide, and his eventual death leaves Horatio behind in this world, whose sorrow is abruptly disrupted by Fortinbras' arrival: "You from the Polack wars, and you from England, / Are here arrived, give order that these bodies / High on a stage be placed to the view" (line 418-20).[14] It seems that Hamlet's eventual participation in the system is an inevitable result of political pressures. Notably, in the last scene before Hamlet's revenge, his woe for Ophelia starkly contradicts his insult of her in Act 3, Scene 1. It also took Hamlet long to recognize that the corpse was Ophelia's: he showed an unusual sense of empathy and persistence to mourn for the dead body despite the gravedigger's repeated disregard, which eventually leads to Laertes' curse on him for Ophelia's death. Indeed, it has been a constant debate whether Hamlet is pathologically mad, with no answer determined. I believe that the elusiveness of Hamlet's madness and the moments of its determination are exactly an illustration of the systematic repression of people that prompt them to struggle to find a way out, that make them believe in their own value while scared to claim it. The uncertain madness of this oft-analyzed character represents the dehumanizing oppression that drives people to lose who they are.

The change from the First Quarto of *Hamlet* to the Folio further proves that an individual's agency is intentionally left vague in the latter versions of this play, leaving readers to wonder whether any act of determination is truly useful. In the First Quarto, for example, there were still lines that clearly indicate one's stance. As Gertrude tells Hamlet, "But as I have a soul, I swear by heaven, I never knew of this horrid murder" (Scene 11, 2520.2).[26] In contrast, in the Second Quarto and the Folio leave Gertrude's innocence of murder in suspense.

Similarly, the lying flat movement is not an outwardly rebellious movement, nor is it just a movement of complete unchanging silence. While the term "lying flat" is still censored by the CCP, images, videos, advertisements, and other derivative media forms of this term are continue to be prevalent on the Chinese internet, such as RedNote, a digital platform popular among Chinese youth.[27] Many of these images are not the rallying chants of rebels, but rather idly depict users' state of mind: they want to travel, they desire a break, and they question what their roles are in the capitalist society, etc. (Figure 1).

Figure. 1 Search results for "躺平 (Lying Flat)" on RedNote[28]

CONCLUSION

This essay informs the role that *Hamlet* plays in modern work culture in China, which tends to mechanize and assimilate people cyclically. Through introducing the tradition of giving up in human history and contextualizing the development of China as the world factory under the CCP, the research highlights the unique similarity between China's sense of quitting and the disjointment of time and identity in *Hamlet*. Specifically, *Hamlet* represents characteristics of China's lying flat movement born under the class struggles, the strict censorship of the CCP, and the historical collective work culture of the country. *Hamlet*—packed full of its pauses, delays, and contemplation—retains its appeal with the modern Chinese audience even despite a language barrier as it reminds people that hesitation can be a form of resistance against the assimilation of identity under empty, social progress narratives. Similar to the lying flat movement in China, characters in *Hamlet* choose to "lie flat" many times during their revenge schemes, driven off course as they ponder over their identities. Just as the characters grow weary of cyclic revenge in *Hamlet*, the repetitive reforms in China find people becoming increasingly suspicious toward their intentions, causing them to ditch their hope for progress entirely, placing themselves in a uniquely human (or perhaps uniquely Chinese) postmodern condition where they opt out of the collective. Their acts, sometimes quiet and small, signify humans' resilience in face of the pressures from modern society. Yet, notably, Hamlet's eventual commitment to revenge warns against the cycle of progress and action, reminding readers of the inescapable pressure of capitalist work culture that aims to assimilate identities.

The play should not only provoke the contemporary Chinese audience, but also global readers to think about who we are in a time where economic progress takes the central stage of social development, where propaganda is repetitive and endless, where workers' identities are assimilated and fungible, and where people long to give up but can't entirely due to realistic considerations. The silence in lying flat, in not engaging with the system, becomes a new, feasible way of protest. The larger research that informs this literary analysis raises questions in political and labor theory about how our current society is failing the people with its sole focus on economic development, and it also turns to mental health studies to learn best how to tackle the political pressures placed on our lives right now. Further research can be done in analyzing the political effects of such lying flat protests. Admittedly, conforming to the capitalist standards of economic progress and work success is still a predominant part of many of our lives, but reading the enduring appeal of *Hamlet* in current Chinese society (and others) can help people to value the hesitation and the lying flat moments in life for us all to contemplate where (and who) we are.

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PRESS SUMMARY

Many have defined Hamlet as an indecisive person, having multiple chances to seek revenge for his murdered father while not doing so. Past literature has also described him as mad, trapped in a cycle of revenge, losing track of time. However, read in the context of China's lying flat movement, Hamlet's hesitation might signal a silent form of resistance. In this movement, Chinese people "lie flat" – refusing to work and choosing alternative lifestyles – to signal a break from the cyclic propaganda of the Chinese Communist Party government for hard work, progress, and collective success. Hamlet, too, breaks himself away from the taking of power in his family and country. His bizarre actions prompt the audience to think about the effects of cyclical, oppressive narratives we now experience: What are their effects on our psyche? How can the politically powerless resist it?

Qualitative Analysis of Medical Students' Speeches at Memorial Services for Body Donors

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ABSTRACT
Student speeches are a common component at medical school memorial ceremonies for body donors. Although some individual speeches have been published, there is no available research on the content within them. This study qualitatively analyzed medical students' speeches in 28 recorded services retrieved from medical school websites. Qualitative thematic analysis was used to quantify the number of speeches (138), the length of speeches, and the number of memorialized donors (3,004). Six themes emerged from the data: (1) Each donor's sacrifice impacts learning and future patient care; (2) The donors' loved ones deserve recognition; (3) The donors are "first patients" and teachers; (4) Students feel a duty to their donors; (5) Human anatomy is unique and complex; (6) Life is finite. The results of this study demonstrated that dissection provided an awareness of mortality and beneficial anatomical knowledge for medical students, which would enhance their care towards future patients. The ceremonies allowed students to humanize their donors by providing them an opportunity to acknowledge the donors' sacrifice and honor the donors' loved ones. This study supports dissection being considered a critical educational experience.

KEYWORDS
Memorial; Anatomy; Dissection; Body donors; Mortality; Education; Medical school; Qualitative

INTRODUCTION

It is a common, longstanding tradition for anatomy programs at medical schools in the United States to hold memorial ceremonies for body donors. According to the literature, the earliest recorded memorial ceremonies were held in the 1980s by Wright State University's School of Medicine and the University of Massachusetts Medical School.[1, 2] By 2013, over 90% of human anatomy programs at medical schools held memorial ceremonies, with most (75%) of those having hosted ceremonies consistently for 10 to 20 years.[3]

There are several common components to memorial ceremonies for body donors. They tend to be organized primarily by students and are attended by students, faculty, and staff.[3] Over half (68%) of medical schools also report inviting family members of body donors.[3] Most ceremonies include speeches with a variety of other elements, such as poetry reading, dancing, candle lighting, and displaying the names and photographs of the donors.[2-10]

Memorial ceremonies provide numerous benefits for both students and donors' loved ones. Although students tend to detach from the donors' humanity during the dissection process,[11-13] research suggests that memorial ceremonies help to restore students' view of the donors' personhood.[6, 14, 15] Memorials also enhance students' appreciation for the donors,[6, 14, 15] enable them to process complex emotions about mortality,[10] and allow them to find closure.[2, 10] The donors' loved ones can also find a sense of closure[15] from the memorial ceremonies by learning the value of the donation.[2, 15] Given the benefits, experts have recommended memorial ceremonies as a best practice for anatomy programs.[16-19]

There is a need to analyze common themes among medical students' speeches from body donor memorial services. Although students' speeches given at memorial ceremonies have been published, there is a lack of research on the common themes found within those speeches. Individual student speeches that were given at the Yale School of Medicine[5-9] and the Mayo Clinic College of Medicine and Science[20, 21] have been published in peer-reviewed journals over the years. Though these publications preserve the words spoken at donor memorial services, no research has analyzed the individual speeches or identified common themes among them across different medical institutions. Previous research on medical school body donor memorial services consists of faculty observation and reflection of the memorial services,[2,10] interviews of students about emotional and learning experiences

from the memorials,[14] and open-ended survey items that invited students to reflect on the effects of the memorials.[15] Granted, there is a benefit of analyzing medical students' responses to interview and open-ended questions; however, given that scholars have analyzed eulogies to understand how people frame death (i.e., organize experiences and action from death) and make sense of death (i.e., give some type of meaning to death),[22] there is also a benefit, and need, for a deeper analysis of how medical students frame and make sense of their experiences through their speeches given during anatomy memorial ceremonies. As such, this study aimed to answer the research question: "What are the major themes within medical students' speeches during body donor memorial services that might frame and make sense of the dissection process?"

METHODS AND PROCEDURES

Prior to data retrieval, this study was approved by Appalachian State University's IRB (study # HS-24-159).

In September of 2023, the anatomical gift program websites from each Doctor of Medicine and Doctor of Osteopathic Medicine school in the United States were searched for donor memorial services. Publicly available online services on program websites were included in the study. For each service, the number of student speeches, the length of time for each speech, and the number of donors who were honored in the memorials were noted.

Methods common to basic qualitative thematic analysis were used to analyze the students' speeches. Thematic analysis is a type of qualitative approach used for discovering and categorizing themes (i.e., repeated patterns) across a data set.[23] Braun & Clarke's six steps for thematic analysis were conducted by: (1) inspecting the data (during and after data collection) through data "immersion"[24] and taking notes of common patterns, (2) working together[25] to create the initial codebook via inductive coding (i.e., coding patterns that emerge from the data and not from preconceived ideas or existing frameworks)[23] while considering both the "manifest content" (i.e., the actual words in the speeches) and the "latent content" (i.e., the underlying meaning of the words),[26] (3) sorting codes to identify, define, and refine the overarching themes that emerged (i.e., "crystallization" of themes),[24] (4) reevaluating the themes, (5) solidifying and defining the themes, and (6) selecting quotes from the data to exemplify each theme.[23, 27]

The coding process was conducted in two phases. First, the student researchers and faculty mentor initially worked together to create a codebook by identifying, defining, and refining the overarching themes that emerged (i.e., "crystallization" of themes).[24] Second, each student researcher used the codebook to code half of the speeches using Microsoft Word. Whenever a student researcher was uncertain of a code to use during the coding process, they resolved the issue through discussion with each other and the faculty mentor to reach consensus.[28-30] All identifying information was removed from the data (i.e., the names of donors, students, family members). During the coding process, it was estimated that "saturation" (i.e., when distinct themes no longer emerge from the data)[31] took place during the fifth memorial service. The researchers also tallied the frequency of themes found in each speech.

RESULTS

A total of 28 online ceremonies were included in the study. Of those, 17 (61%) included the names or specified the number of donors who were honored at the ceremonies, for a total of 3,004 donors. For this study, there were a total of 138 student speeches, varying in length, with a total of 4 hours and 45 minutes of speeches analyzed (**Table 1**).

Medical School	Donors	Speeches	Total Time
Alabama College of Osteopathic Medicine	*	12	15 min 47 sec
Albany Medical College	207	5	25 min 29 sec
Augusta University	107	9	22 min 24 sec
Burrell College of Osteopathic Medicine	*	5	9 min 30 sec
Creighton University	*	12	5 min 15 sec
Kansas City University College of Osteopathic Medicine	54	6	7 min 40 sec
Kansas University	*	2	6 min 42 sec
Mayo Clinic Alix School of Medicine	203	4	7 min 57 sec
Northeast Ohio Alix School of Medicine	53	1	52 sec
SUNY Upstate Medical University	*	1	1 min 30 sec
University of Alabama at Birmingham	462	2	4 min 4 sec
University of Arizona	62	2	2 min 38 sec
University of Buffalo	*	21	18 min 7 sec
University of California, Irvine	*	4	16 min 27 sec
University of California, Los Angeles	216	5	15 min 18 sec

University of California, San Diego	*	11	17 min 9 sec
University of Cincinnati	104	3	11 min 48 sec
University of Hawaii Manoa	126	4	8 min 17 sec
University of Indiana	*	4	16 min 24 sec
University of Iowa	192	6	25 min 13 sec
University of Minnesota	506	4	7 min 10 sec
University of Mississippi	112	3	4 min 40 sec
University of Nevada Reno	*	1	3 min 2 sec
University of Toledo	181	2	4 min 53 sec
Washington University in St. Louis	130	3	7 min 29 sec
Wayne State University	254	2	9 min 30 sec
Western University of Health Sciences - College of Osteopathic Medicine of the Pacific	35	2	5 min 20 sec
Wright State University	*	2	4 min 41 sec
Total	3,004	138	4 hr 45 min

Table 1. The medical school's number of donors, number of speeches, and total duration of speeches. *Not specified during the memorial

From the qualitative analysis, six major themes emerged from the data: (1) Each donor's sacrifice impacts learning and future patient care; (2) The donors' loved ones deserve recognition; (3) The donors are teachers and first patients; (4) Students feel a duty to their donors; (5) Human anatomy is unique and complex; (6) Life is finite.

Along with each theme description below, four representative quotes are provided with italicized words that reinforce the theme's meaning.

Theme #1: Each donor's sacrifice impacts learning and future patient care

The most prevalent theme among the student speeches was that each body donor had a vast effect within the healthcare system. Each donor directly impacted the education of the students dissecting them and indirectly impacted every future person those medical students helped once they became doctors. The longevity of a donor's sacrifice stretched far beyond the dissection lab and affected the health of each living person aided by future physicians. This theme was found in 88 (63%) of the speeches.

"*Your gift will keep going* through time and space with a broad, deep, and untold ripple effect. *So many lives will be impacted as future patients and doctors intersect.*" (Northeast Ohio Medical University, Student)

"Over the next thirty years, this contribution, *this incredible gift, is going to impact thousands and thousands of patients that we're going to encounter.*" (Wright State University, Third-year student)

"The generous donations *allow us to provide better care for our future patients* and become better health care providers." (University of Minnesota, First-year student)

"Not only did you [donor] impact the lives of every person sitting in front of me who came to celebrate your life, *you somehow managed to impact the lives of hundreds of people you never met*, and you did so after you passed." (University of Arizona, Third-year student)

Theme #2: The donors' loved ones deserve recognition

During the services, many students acknowledged the sacrifice made by the donors' families and friends. While not giving up their own bodies, parting with a loved one soon after death was not without challenges, especially knowing strangers studied and dissected them. The loved ones had an important role in each donor's life before and after death, and their generosity was worthy of appreciation. This theme was found in 70 (50%) of the speeches.

"I wholeheartedly express gratitude for you [families] having the strength to be present today while you still may be grieving the loss of your loved ones." (University of Indiana, First-year student)

"For the bounty of knowledge gained from the (donor) patients, we say thank you. *We express our appreciation of families, friends, and loved ones who have placed their trust in us.*" (Western University of Health Sciences - College of Osteopathic Medicine of the Pacific, First-year student & class president)

"*Their donation would not have been possible without you [family]*." (University of Mississippi, Student)

"I just want to take this opportunity to *thank each and every one of the family members of all the donors to the anatomy lab*." (University of Creighton, Student)

Theme #3: The donors are "first patients" and teachers
A common theme was that the donors were the medical students' "first patients." Not only did the donors act as bodies to dissect, but they were also true teachers to learn from, showing the students aspects of anatomy and medicine that textbooks, diagrams, and lectures never could. This theme was found in 60 (43%) of the speeches.

"Your loved ones *were our greatest teachers; they were the ones who helped us see inside*." (Northeast Ohio Medical University, Student)

"Each student that has walked into the anatomy lab at KCU has *the honor of learning from their first ever patient*, the individual who so graciously donated their body. These individuals who donated their bodies have *taught us much more than about what the anatomy of their body contains*." (Kansas City University College of Osteopathic Medicine, Student anatomy fellow)

"The thing that really stays close to heart is that your loved one was *our first patient that we'll never forget*." (Wright State University, Third-year student)

"*You [donor] are my teacher* throughout my first year of medical school." (University of Arizona, Third-year student)

Theme #4: Students feel a duty to their donors
Another recurring sentiment was that since a stranger gave themselves to aid the students' learning, they often felt apprehensive and underqualified to work on the donor's body. This charged them with an obligation to treat their donors in a venerable way through meticulous and respectful dissection. They felt the need to make the donor's gift worthwhile by not squandering the opportunity given to them in the lab. This theme was found in 56 (40%) of the speeches.

"It wasn't merely raw knowledge that was gained...*we also learned how to care, how to respect [the donors]*." (Kansas City University College of Osteopathic Medicine, Student)

"Every action taken in the lab was not a simple pursuit of fact, but *in respect for the gift that was given to us*." (Burrell College of Osteopathic Medicine, First-year student)

"I remember how humbling it was on our very first day of anatomy … someone who had trusted our institution with the donation of their body trusted us with everything they had left to give to this world, trusted us with their final gift. That moment to me felt heavy. In fact, that entire week felt heavy, and it should *because a gift like that should not be taken lightly*." (University of Iowa, Second-year student)

"*I was uneasy and a bit nervous* about how we could balance understanding the beauty and complexity of the human body while also *honoring this amazing soul*." (University of Buffalo, Former student)

Theme #5: Human anatomy is unique and complex
The students' speeches frequently mentioned that the donors' anatomy was unique and complex. Each person had a history and body specific to themselves. Working with donors showed the medical students that future patients would not perfectly align with textbook drawings, but would rather be individualized and complicated. This theme was found in 48 (34%) of the speeches.

"As much as we appreciate all that we can learn from our books, pictures, and million-dollar simulations that our school provides, *nothing can compare to having an actual person with whom to work*." (University of Cincinnati, Second-year student)

"*I learned about the complexity of human lives*, the working parts that make each and every one of us unique but also the same." (Indiana University, First-year student)

"It has always been taught to me through texts and drawings and textbooks. But *the opportunity to learn anatomical structures through actually holding them and seeing them has enhanced my education in a significant way*." (Mayo Clinic Alix School of Medicine, First-year student)

"*Learning about the complexity of how we're designed* made me realize how many things have to go right in order for me to even be alive" (Indiana University, First-year student)

Theme #6: Life is finite

This theme featured students' acknowledgment that life is fleeting. Many students referenced death as being made real to them in the anatomy lab when they were confronted with mortality every time they worked with the deceased. Students wondered who the donors were as people and the lives they lived before passing away. This theme was found in 32 (23%) of the speeches.

"*Through death, our donors were able to bring our class to life.*" (University of Nevada Reno, First-year student & class president)

"You [donor] are the wisdom that death is the greatest invention of life, that the old returns to the earth and the stars and it cycles anew…and that how I live will determine whether I cower in regret *when death greets me*…or smirk bravely without remorse." (University of San Diego California, Student)

"He [donor] was a son to someone, likely a friend to many others. He may have been a sibling, a spouse, or a dad. Maybe a grandfather or a great-grandfather. We didn't know much, but we [the lab group] knew *he had spent 72 years on this earth. That was 50 more years than I had been alive at that time.*" (University of Buffalo, Student)

"*In the history of the earth, our lives are half a letter in an immense novel.*" (University of Hawaii Manoa, First-year student)

DISCUSSION

This study sought to explore the common themes found within medical students' speeches from 28 medical schools' online body donor memorial services. The qualitative, thematic analysis found six themes, in which students framed and made sense of the body donor, the donors' families, and the learning that took place through the dissection process. While previous observations, focus group interviews, and surveys found that memorial services help students to appreciate donors, view the donors as people, and process concepts about mortality,[6, 10, 14, 15] this study added to the body of research in that memorials may enhance students' perspective that donors are teachers/patients that can impact learning and future patient care, appreciation for donors' loved ones, and understanding that human anatomy has unique attributes for each person.

The findings from this study indicate that the dissection process was valuable for students in learning anatomy and can have numerous, wide-ranging, positive impacts on their future patients. This reflects other qualitative studies about students' experiences when dissecting donors. Specifically, students have reported that dissection was a critical component for learning anatomy, as it provided a thorough, hands-on experience when compared to learning from textbooks or diagrams,[12, 32] which could then be used to help their patients in the future.[33] As such, the findings from this study align with other scholars' views in the debate regarding the continued use of donor dissection for medical school training, as compared to the use of computer technology for teaching anatomy.[34, 35] What is unique to the current study is that memorial services may help to emphasize this to students beyond the dissection laboratory experience.

The findings from this study also mirror previous research regarding the impact of memorials on students' humanization of donors. Prior research shows that medical students tend to detach from their donors during dissection.[11-13] Memorials for donors have been shown to be beneficial because they allow students to restore a view of the donors' humanity by emphasizing donor personhood through testimonies and engaging with the donors' loved ones.[6, 14, 15] This study indicates that ceremonies provide students with an opportunity to outwardly express the emotions that they tend to feel during the dissection process, including gratitude towards the donors,[12, 32, 36, 37] and a sense that donors were both their teachers and their "first patients."[13, 32, 38]

The students' speeches in this study indicated that dissecting body donors led to students contemplating death. Previous studies have also found that students have thoughts of mortality during dissection.[11-13, 32] This supports medical schools hosting memorial ceremonies for students to express their thoughts about death. The findings also support experts' recommendations that anatomy instructors provide space for students to process their emotions about death and dying before and during dissection, given the nature of anatomy laboratories and the constant exposure to the dead.[39-42]

Importantly, this study adds to the literature in that memorials to body donors have the potential to enhance medical students' appreciation for the family of body donors. The existing literature on body donor memorials have not shown students' views towards the donors' loved ones. Yet, students' speeches emphasize those who were related to, or had a deep connection to, the body donor. This reflects eulogy research on social discourse of relational identity, meaning that eulogists may extend gratitude to those who attend a memorial service.[22] In addition, students' speeches indicate that each donor underscored that actual anatomy may be different compared to other people and textbook illustrations.

There were limitations to this study. First, the memorial ceremonies included in this research were only from videos provided on medical school websites. Future studies on this topic may want to include ceremonies on other online video sharing platforms, such as YouTube.com.[4] Second, the ceremonies were recorded between 2019 to 2023, which may have been due to recording funeral services becoming more common during the COVID-19 pandemic.[43] Since this study was limited to recorded memorial services that were from recent years, future studies could compare the themes seen in these services to those found in services from previous or future years. Third, given the qualitative nature of the study, the results are not generalizable to all memorial ceremonies; however, the results may still be "transferable"[44] to ceremonies that have similar contexts. Fourth, this study did not analyze the words of faculty members, music, or poetry presented in these services. Further research could be conducted on these aspects of memorial services, as they may convey additional findings to those reported in this study. Finally, it is worth noting that since popular forms of artificial intelligence (AI) were in existence during the study's timeframe and commonly used as a form of ghostwriting,[45] it is possible that speeches analyzed for this study may have been wholly or partially composed by AI and not organically written by the students.

CONCLUSIONS

This study qualitatively analyzed medical students' speeches given during online memorial ceremonies for body donors. Common themes of mortality, the uniqueness of human anatomy, and the donors being selfless first patients and teachers were seen, indicating the gratitude possessed by medical students for their donors and the importance of dissection labs for their education. The findings from this study add to the literature, and also align with previous research that memorial services aid students in finding closure and humanizing their donors, supporting that the dissection process is valuable in teaching anatomy to medical students.

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PRESS SUMMARY

Medical students regularly give speeches at memorial ceremonies honoring the individuals who donated their bodies for medical education. However, there is no published research that has analyzed what is expressed in these speeches, and this paper aims to fill that gap. We analyzed 138 student speeches from 28 ceremonies to understand what future doctors took away from the human dissection experience. Six key themes emerged, including a deep respect for the donors, a recognition of the donors' families, the donors being the students' first patients, and a strong sense of responsibility. Students also expressed how the anatomy lab helped them appreciate the complexity of the human body and grapple with mortality. Our findings support that the act of dissection and these ceremonies are more than just anatomically educational; they offer a complex, emotional experience that aids in shaping more competent and compassionate doctors.

Tritium Production from Nitrogen in a Tokomak Reactor Resulting from a Neutron Source

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ABSTRACT
Tritium is an important isotope of hydrogen used in deuterium-tritium (D-T) fuel in nuclear fusion reactors, but it is only naturally occurring on Earth in the upper atmosphere resulting from galactic cosmic radiation (GCR) interactions, which produces small amounts of tritium. This poses a problem because tritium is an important component for nuclear fusion reactors that utilize deuterium-tritium (D-T) fuel. This study investigates tritium production by applying the nuclear reaction resulting from GCR interactions and a mathematical model for the flux of neutrons that reflect the energy levels associated with the resulting neutrons from D-T reactions to a two-dimensional domain representing the tritium production layer in a tokomak reactor. The results of this study indicate that for a feasible amount of tritium production, the nitrogen density must be exceptionally higher than that of nitrogen gas. As such, GCR interactions do not produce a feasible source of tritium production for D-T fuel.

KEYWORDS
Galactic Cosmic Rays; Tokamak; Tritium; Neutron; Neutron Diffusion; Nuclear Fission; Tritium Breeding Ratio; Tritium Production

INTRODUCTION

Tritium is a radioactive isotope of hydrogen that is rare on Earth with few natural sources, including galactic cosmic ray (GCR) interactions in the upper atmosphere.[1] GCRs are composed of highly accelerated light particles, mostly protons and neutrons, that collide with particles in the upper atmosphere.[2] Interactions of this nature cause the formation of tritium by a neutron, from the GCR, colliding with a nitrogen atom, and can be shown by the reaction equation,

$$ {}^{14}_{7}N + {}^{1}_{0}n \longrightarrow {}^{12}_{6}C + {}^{3}_{1}H\,, \qquad \textbf{Equation 1.} $$

where ${}^{14}_{7}N$ is nitrogen, ${}^{1}_{0}n$ is the neutron from the GCR, ${}^{12}_{6}C$ is carbon, and ${}^{3}_{1}H$ is the tritium.[1] In addition to the natural fission reaction described by this equation, tritium is also produced artificially in nuclear reactors because of its usefulness in tokomak fusion reactors.

Tokomak fusion reactors are toroidal shaped nuclear reactors designed to confine plasma using magnetic fields. The plasma for these reactors can consist of deuterium-deuterium (D-D) fuel or deuterium-tritium (D-T) fuel. Deuterium is a non-radioactive isotope of hydrogen that is present in large concentrations in sea water.[3] While deuterium is more abundant on Earth than tritium, the energy production associated with D-D fuel is only 3.27 MeV whereas it's 17.7 MeV for D-T fuel.[3] Additionally, the reaction cross section of D-T fusion is markedly higher at lower temperatures as compared to D-D fusion.[4] Therefore, artificially producing tritium is an important consideration for tokomak reactors.

To accomplish tritium production in tokomak reactors, a lithium plasma-facing component is typically incorporated into the reactor which acts as a source to artificially produce tritium. This is termed a breeding blanket and has been shown to significantly improve the reactors performance.[5] Lithium is an extremely reactive metal with a relatively low melting temperature, and the breeding blanket layer is designed to evaporate and ionize, allowing neutrons to regularly collide into the lithium ions.[5] This collision produces a fission reaction resulting in a byproduct of tritium.

The work contained herein investigates applying the reaction in **Equation 1** to a 2D, rectangular domain (see **Figure 1**) simulating a breeding zone of a tokomak reactor. A literature review reveals this application of atmospheric tritium production as a breeding method for fusion reactors as original, although the use of GCRs to create nuclear fuel for lunar fission reactors has been previously considered.[6] The domain herein is simplified to be a medium consisting solely of nitrogen atoms, and is subjected

to an incoming neutron source that reflects the energy levels of the neutrons from D-T fuel reactions. These neutrons move into the domain and collide with the nitrogen to form tritium. This paper describes the theoretical construction of the model, application to the domain, and resulting amount of tritium produced.

THEOERTICAL BACKGROUND

The kinetic theory of gases describes the movement of particles and can be used to build a model for the movement of neutrons. When applied to the domain of a simplified breeding zone of a tokomak reactor, tritium produced resulting from neutron collisions can be investigated. This motion is governed by the Boltzmann transport equation and can be written as,

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_V N\mathrm{d}^3\boldsymbol{r} = \int_V S\mathrm{d}^3\boldsymbol{r} - \int_V N\boldsymbol{v}\Sigma_c\mathrm{d}^3\boldsymbol{r} - \oint \boldsymbol{J}\cdot\boldsymbol{n}\mathrm{d}A, \qquad \textbf{Equation 2.}$$

where N describes the velocity distribution function, V is the volume for which the equation is applicable, $\boldsymbol{r}$ is the position vector, S is the source being added, $\boldsymbol{v}$ is the velocity, Σ_c is the macroscopic reaction cross section of radiation capture (which allows one to determine the likelihood a reaction will occur), $\boldsymbol{J}$ is the source being lost, and t is time.[7] This equation represents the general motion of a particle due to any external sources, intermolecular interactions, and advection. It can be simplified by imposing a diffusion approximation based on Fick's Laws of Diffusion forcing the neutrons to transport solely via diffusion.

This is accomplished by imposing that there are no strong point sources of neutrons within the medium which the neutrons interact, resulting in a uniform distribution of nitrogen. With this uniform distribution, Σ_c becomes independent of the position of the neutron in the domain.[7] Furthermore, for the purposes of this analysis, neutron collisions are assumed to occur isotropically and particle scattering is assumed to be elastic. This implies that the resulting neutron has the same energy as the incoming neutron.[8] Additionally, focusing on the steady state dynamics of a cross-section of the breeding blanket without any flux discontinuities, **Equation 2** can be simplified to the following in a Cartesian coordinate system,

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} - \frac{\Sigma_c}{D}\phi = \frac{-S}{D}, \qquad \textbf{Equation 3.}$$

where ϕ is the neutron flux, S is a neutron source, and D is the diffusion coefficient defined as,

$$D = \frac{\Sigma_s}{3\Sigma_t^2}, \qquad \textbf{Equation 4.}$$

where Σ_s is the elastic scattering macroscopic interaction cross section, and Σ_t is the total macroscopic interaction cross section.[7]

Solving **Equation 3** for the neutron flux allows the tritium breeding ratio (TBR) to be calculated. The TBR is used in nuclear fusion reactor analysis to ensure there is enough tritium being produced to sustain the system. It can describe the amount of tritium produced over the amount of tritium fused, and can be written as,[9]

$$TBR = \frac{\int \Sigma_c\phi\mathrm{d}V}{\int S\mathrm{d}V}. \qquad \textbf{Equation 5.}$$

When ϕ as a function of location in the domain is determined via **Equation 3**, the TBR can be calculated to determine if the tritium production method from a given neutron source is feasible. The macroscopic cross sections used in this analysis (Σ_c, Σ_s, and Σ_t) are calculated from the microscopic cross sections,

$$\Sigma = \sigma N, \qquad \textbf{Equation 6.}$$

where Σ is the macroscopic cross section, σ is the microscopic cross section, and N is the atomic number density, defined as,

$$N = \frac{\rho_N N_A}{M}, \qquad \textbf{Equation 7.}$$

where ρ_N is the nitrogen density, N_A is Avogadro's number, and M is the molar mass of nitrogen.[10]

MODEL APPLICATION

The neutron flux into a medium of nitrogen resulting in the neutron-nitrogen reactions described in **Equation 3** is applied to the domain depicted in **Figure 1**. To maintain independence on the physical size of the domain, Neumann conditions were applied to the domain's boundary. However, to simulate neutrons interacting with the breeding blanket modelled by this domain, one

portion of a boundary had a Dirichlet condition imposed representing an inlet of neutrons entering the system. Since steady state dynamics are of interest, this condition represents a constant neutron source. To completely define the domain, w, l, and a were chosen to be 0.5 cm, 0.5 cm, and 0.0526 cm respectively.

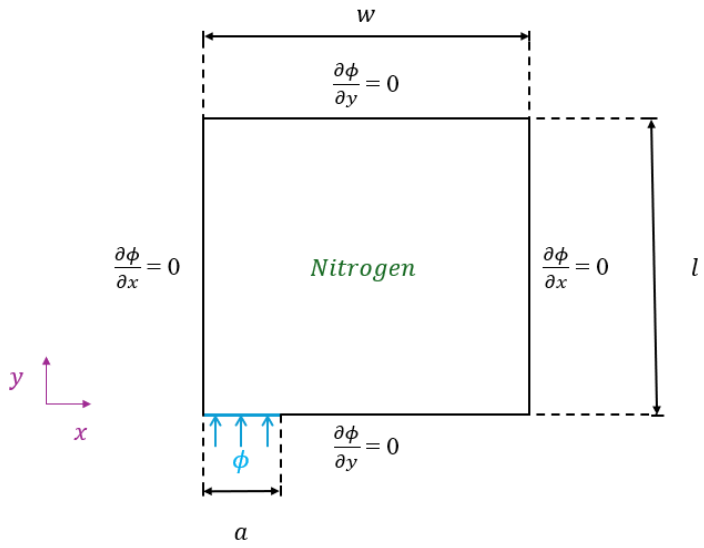


Figure 1. A schematic of the domain representing the breeding blanket. The bottom left corner of the domain has a constant flux source representing neutrons entering the domain whereas the other boundaries only define the derivatives of the flux allowing any value of flux to exist, effectively making the physical domain size *w* by *l* irrelevant.

It should be noted that the source terms in **Equations 3** and **5** need not be the same. Specifically, S in **Equation 3** may be defined as a description of the system with respect to the neutron multiplication factor. This multiplication factor describes the ratio of the number of neutrons over time adjacent generations.[11] This can take one of three different cases, subcritical, critical, or supercritical. Here, the neutron multiplication factor was taken to be subcritical because the amount of neutrons in the system is decreasing as the reactions described by **Equation 1** occur. Additionally, by focusing on steady state dynamics, generational dependency can be neglected, and therefore the multiplication factor can be considered constant.[11] This source definition accounts for the probability of a neutron to be captured in the domain because Σ_c is included, and can be written as,

$$S = \Sigma_c k_{\text{mult}} \phi \,, \qquad \textbf{Equation 8.}$$

where k_{mult} is the neutron source multiplication factor.[7] Since the multiplication factor was taken to be subcritical and the containment material is taken to be C45, the neutron source multiplication factor is taken to be $k_{\text{mult}} = 0.99273$.[11]

The source in **Equation 5** represents the fusion neutron source i.e., the neutrons produced from fusion reactions. As the mathematical model does not have a formal fusion neutron source, the Dirichlet boundary condition can be considered as this source. In other words, the constant inlet of ϕ for a length of a at $y = 0$ is treated as the inlet from a fusion reactor source, similar to lithium breeding blankets being a plasma-facing component in a tokomak reactor. However, it should be noted that by defining the S of **Equation 5** in this way, the ratio is no longer a breeding ratio as this analysis does not consider the tritium that is fused because there are no fusion reactions in the domain of analysis. This new ratio can be described as a tritium production ratio (TPR), quantifying the amount of tritium produced per neutrons entering the system.

The boundary conditions depicted in **Figure 1** may be written as,

$$\left.\begin{matrix}\phi_x(0,y) = 0 \\ \phi_x(w,y) = 0\end{matrix}\right\} \text{ for } 0 < y < l, \qquad \textbf{Equation 9a.}$$

$$\phi_y(x,l) = 0 \quad \text{for} \quad 0 < x < w, \qquad \textbf{Equation 9b.}$$

$$\left.\begin{matrix}\phi(x,0) = 0 \\ \phi_y(x,0) = 0\end{matrix}\right\} \text{ for } \begin{matrix}0 < x < a \\ a < x < w.\end{matrix} \qquad \textbf{Equation 9c.}$$

Imposing these on **Equation 3** results in a solution for ϕ over the domain. Due to the elliptic behavior of **Equation 3**, an analytical solution can be obtained using the method of separation of variables (an example of which can be found in **Section 9.4** of **Reference 12**) resulting in,[13]

$$\phi(x,y) = \sum_{p=0}^{\infty} C_p \cos\left(\frac{p\pi}{w}x\right)\cos\left(\sqrt{\frac{\Sigma_c}{D}(k_{\text{mult}}-1) - \left(\frac{p\pi}{w}\right)^2}\, y\right), \quad \textbf{Equation 10.}$$

where C_p is defined at $y = 0$ as,

$$C_p = \begin{cases} nv_n & \text{when} \quad 0 \le x \le a \\ 1 & \text{when} \quad a < x \le w \end{cases},$$

and n is the neutron density, and v_n is the neutron velocity defined as,

$$v_n = \sqrt{\frac{8kT}{\pi m}}, \quad \textbf{Equation 11.}$$

where k is Boltzmann's constant, T is temperature, and m is the mass of a neutron. It should be emphasized that the complete derivation of **Equation 10** can be found in **Reference 13**.

To determine the TPR on the solution domain, the volume integrals in **Equation 5** become area integrals. Furthermore, the area integral in the numerator can be written as a Reimann's summation over the domain and the dominator becomes a simple line integral because of the application of the constant source input. This transforms **Equation 5** into,

$$TPR = \frac{\sum_{i=1}^{w}\sum_{j=1}^{l}\Sigma_c\phi(x_i,y_j)}{anv_n}. \quad \textbf{Equation 12.}$$

RESULTS AND DISCUSSION

To analyze the effect of model parameters on the TPR, a range of neutron densities, nitrogen densities, and temperatures, are imposed upon the system and listed in **Table 1**. The range of neutron densities is based around values of a single impulse from a portable neutron generator which releases 1.5×10^8 neutrons/s at an energy level of 14 MeV,[14] the nitrogen densities cover a range of possibilities for nitrogen gas, and the temperatures correspond to the average temperature of lithium as a plasma facing component of tritium breeding blankets.[4]

T [K]	ϱ_N [g/m^3]	n [neutrons]
400	0.1	1.00E+07
450	1.251	1.25E+08
500	50	1.00E+09
550	100	5.00E+09
600	200	1.00E+10
700	300	1.50E+10
800	400	2.00E+10
900	500	4.00E+10
1000	1000	5.00E+10

Table 1. The range of values for the neutron density (n), nitrogen density (ρ_N), and the temperature (T) used in this study. It should be noted that these values are independent of each other.

The remaining parameters needed to completely define **Equation 10** are σ_c, M, N_A, m, and k. For an energy level of 14.1 MeV, similar to that of the portable neutron generator, the National Nuclear Data Center records that $\sigma_c = 1.679535 \times 10^{-5}$ barns, $\sigma_s = 9.6973995 \times 10^{-1}$ barns, $\sigma_t = 1.5706345$ barns for $^{14}_{7}N$.[15] The solution behavior of **Equation 10** for all cases in **Table 1** exhibit identical trends with differing magnitudes. A small region of high neutron flux due to the boundary condition of **Equation 9c** is clearly visible and rapidly diffuses into the remainder of the domain, seen in **Figure 2**.[13] This is a direct result of only containing transport via diffusion. Furthermore, the neutrons react with the immediately available nitrogen atoms as they move into the domain, so the neutrons are used immediately upon their entry into the system. In other words, the neutrons cannot travel a great distance into the domain because they are being used in reactions with the closest available nitrogen atoms, this in conjunction with the limited transport methods narrows their movement to the immediate vicinity of entrance into the domain.

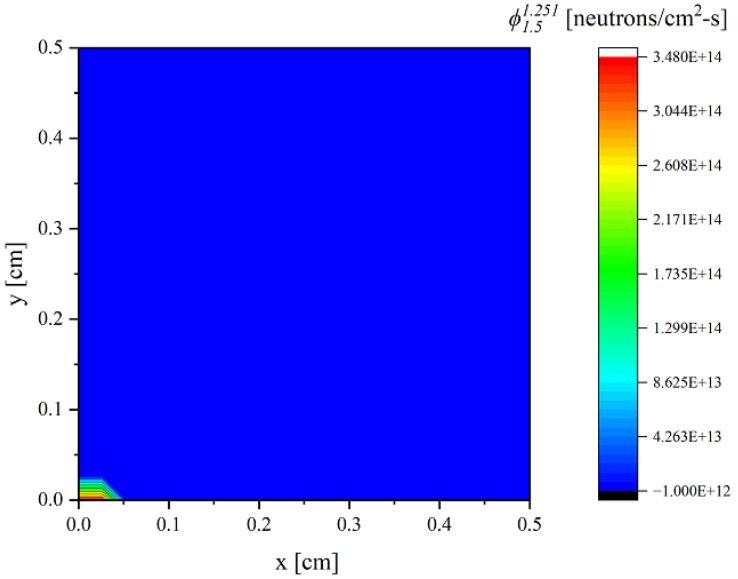
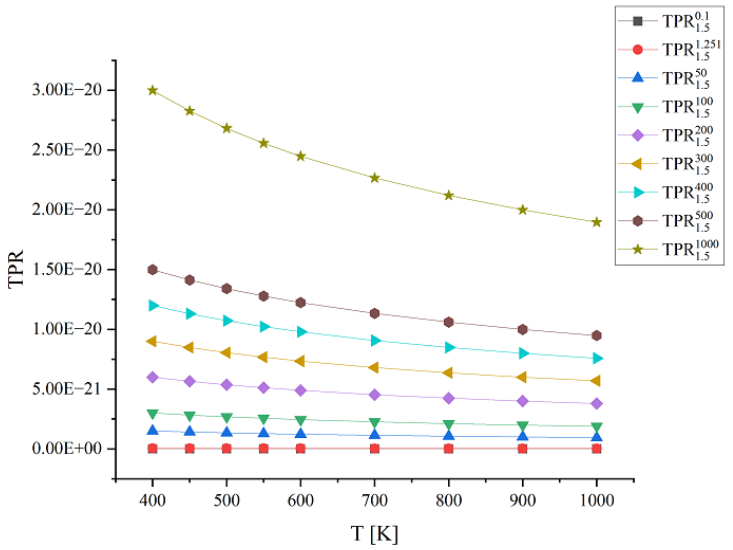


Figure 2. Distribution of the neutron flux in the computational domain for the first temperature case in **Table 1**. The superscript on ϕ indicates the nitrogen density and the subscript represents the neutron density resulting in this specific contour. Additional flux graphs for the other cases outlined in **Table 1** can be found in **Reference 13**.

With ϕ now established over the entire domain, the feasibility of tritium production can be investigated. It's desirable to have $TPR > 1$ which would mean the tritium produced matches the neutrons entering the system. The TPR was determined with **Equation 12** and there was an investigation into the effects of changing nitrogen and neutron densities over a range of temperatures. The nitrogen density has a more significant effect on the TPR values than the neutron density because diffusion only moves the neutrons in a restricted space for all neutron flux cases. Since the overall flux is not significantly impacted by changes in neutron density, the TPR values are not significantly affected either. This can be seen by the TPR values for the varying nitrogen density, as these results are consistently at an order closer to the target TPR than when the neutron density is varied as shown in **Figure 3**.[13] Additionally, the constant neutron density case exhibited results with the same order of magnitude for all nitrogen density cases, whereas at a constant nitrogen density, the results were on different orders of magnitude for the lower and upper neutron density cases.[13] This contrasts from the nitrogen density because as the nitrogen density increases, there are more nitrogen atoms within the space the neutron flux is the highest so there are more opportunities for neutron-nitrogen interactions over the entire computational domain. Furthermore, the neutrons cannot travel far into the domain, due to the limiting factor of diffusion transport. If the neutrons are restricted to the corner of the domain in which they enter, the number of neutrons becomes irrelevant because there is a finite number of nitrogen atoms available in a given space. Therefore, the nitrogen density has a more significant influence on the TPR values than the neutron density does.

The neutron flux nominally permeating into the domain shown in **Figure 2** and subsequent diminished effect of the neutron density as seen in **Figure 3** results from limitations of the current model. In particular, the diffusion approximation imposed on **Equation 2** assumes negligible advection which minimizes the distribution of appreciable neutron flux. Even if neutron transport was governed solely by Fick's Laws of Diffusion as indicated in **Equation 3**, the simplified 2D Cartesian domain itself may mitigate neutron motion. Consider the toroidal shape of a tokomak in comparison to the 2D square shown in **Figure 1**, for example. The toroid would have a much larger surface area at which flux enters the domain as opposed to the line that it enters the 2D square domain. Of course, if neutrons travel further into the computational domain, then the neutron density would have a more appreciable effect than that shown in **Figure 3**. Three-dimensional dynamics incorporating advection would result in a remarkably more complex analytical solution than that found in **Equation 10**, especially if transient dynamics were additionally considered. These model modifications may be best dealt with using a Monte Carlo-type simulation as compared to a deterministic solution highlighted herein. One possibility would be the Monte Carlo N-Particle code developed by Los Alamos National Laboratory.[16] The inclusion of these more realistic constraints is considered a topic for future study.

a)



b)

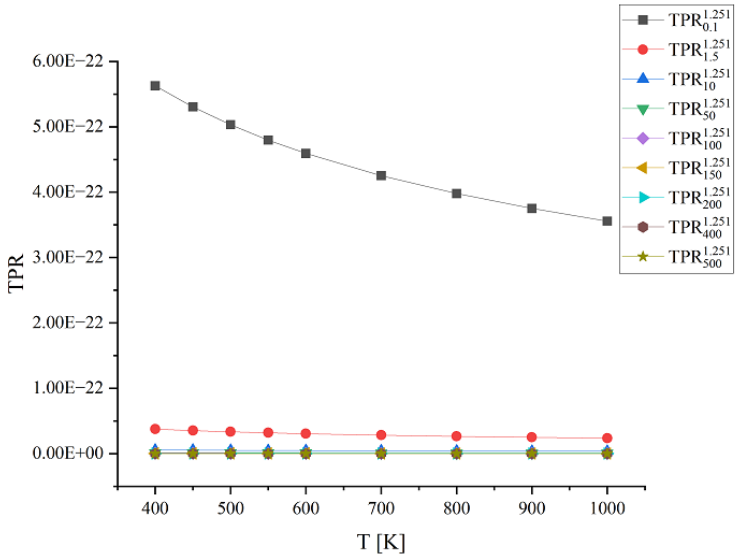


Figure 3. The effects of nitrogen density (a) and neutron density (b) on the TPR. The superscript in the legend indicates nitrogen density and the subscript represents the neutron density for the particular plotted ase. The magnitude of the TPR when changing the nitrogen density indicates that the nitrogen density has more significant effect on the TPR as compared to the neutron density.

Using a baseline of $n = 1.5 \times 10^8$ neutrons and including the multiplication factor of $10^{11.07}$, a contour of the TPR as a function of ρ_N and temperature is depicted in **Figure 4.** As expected, when ρ_N increases, the TPR also increases because there are more nitrogen atoms in the system creating more cross sections i.e., more possibilities for interactions. Additionally, as temperature decreases, TPR increases due to the decrease in microscopic cross-sections for neutrons as energy increases.[15] The increase in kinetic energy would generate more movement on the molecular level, but the neutron cross sections are smaller. This makes the interactions less likely at higher temperatures because the neutron needs to collide with a smaller target to obtain a desired interaction, in this case tritium production. For the current system, to have an appreciable TPR, $\rho_N > 7.5 \times 10^7$ g/cm^3 which is significantly higher than the density of nitrogen gas, again stressing that a single portable neutron source is not a feasible method of producing tritium.

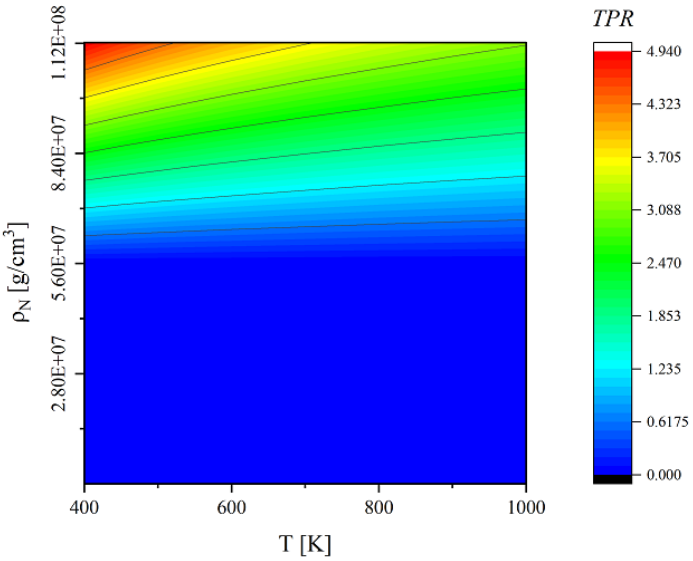


Figure 4. A contour representing the TPR results for a fixed neutron density over the range of temperatures considered in **Table 1**. Tritium production is considered feasible when the value of the TPR is greater than 1.

The TPR resulting from a portable neutron generator produces in an insufficient amount of tritium to be considered a viable source. To obtain feasible values of the TPR, the strength of the neutron generator needs to increase considerably. When a multiplication factor of $10^{11.07}$ is incorporated into **Equation 12**, desirable TPR values are met. It should be emphasized that while this is a large multiplication factor, it simply means the portable neutron generator imposed through **Equation 9c**, will not create a useful amount of tritium on its own for the specified domain and model limitations. This could be altered by incorporating a more realistic 3D domain and particle transport dynamics such as advection. Using that more complex, realistic model, the feasibility of using GCRs for nuclear power in extraterrestrial applications akin to **Reference 6** could be investigated.

CONCLUSION

This study explores applying tritium production reactions from galactic cosmic radiation by imposing an interaction with a portable neutron source and a tritium breeding blanket in D-T fueled tokomak fusion reactors. The neutron flux in a simplified 2D domain was analytically solved for and it was found that the flux does not deeply diffuse into the domain. The tritium production ratio due to this flux was calculated which showed a more significant dependency on the nitrogen density as compared to the neutron density. For a baseline scenario to produce a feasible amount of tritium, the density of nitrogen would need to far exceed the density of nitrogen gas. As such, a portable neutron source is not a feasible method of producing tritium for use in tokomak fusion reactors. This analysis could be modified to incorporate other modes of transport in addition to diffusion, with the intention of promoting further neutron distribution into the system.

ACKNOWLEDGEMENTS

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PRESS SUMMARY

Tritium is an important isotope of hydrogen for the preferred fuel for nuclear fusion reactors, but it is rare on earth. It only occurs naturally in the upper atmosphere due to interactions of nitrogen in the atmosphere with high energy particles from space called galactic cosmic radiation. Because tritium is important for fusion reactors, there are methods to produce tritium inside of the reactor to allow energy production to continue during operation. This paper investigates tritium production with nitrogen to recreate the natural tritium production akin to galactic cosmic radiation reactions inside of a nuclear fusion reactor. The results of this study indicate that this method of tritium production is not sufficient for successful nuclear fusion reactor operation.

Power Outage Duration in Louisiana by Customer Endpoint and Environmental Conditions

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ABSTRACT
Power outages across the United States are increasing in frequency and duration, raising concern about the resilience of critical infrastructure and the operational stability of regional energy systems. Prior work emphasizes system level reliability and severe weather, with limited insight into how local conditions shape outage duration at the distribution edge. This study identifies key associations of annual power outage duration in Louisiana, operationalized as a household level analog of the System Average Duration Index (h-SAIDI). Event correlated outage records, severe weather reports, and parish-scale indicators were integrated for 63 parishes across five biennial intervals (2014-2022). A Gamma generalized linear model with a log link was used to estimate associations, complemented by spatial and distributional analyses. Results indicated that outage duration reflects the interplay of severe weather factors, customer endpoint conditions, and underlying distribution network and restoration dynamics. Parishes with higher mobile home prevalence and severe weather damage exhibited longer annual outage duration. In contrast, unemployment and lack of vehicle access showed negative associations, consistent with the concentration in urbanized service territories characterized by shorter spans and greater switching options. These findings support targeted local resilience strategies across diverse service territories.

KEYWORDS
Power Outage Duration; Grid Resilience; Energy System Reliability, Severe Weather Events; Customer Endpoint Conditions; Household Infrastructure; Parish-level Analysis; Gamma Regression

INTRODUCTION

Power outages are a persistent and costly challenge across the U.S., prompting growing concern over the resilience of energy systems and the reliability of critical infrastructure.[1,2] Secure, reliable grid operations are essential to limiting disruption, economic loss, and human hardship.[1,3,4] Prolonged outages intensify social hardship by disrupting essential services for extended periods.[5] For example, extended power loss can halt refrigeration, disable medical equipment, and interrupt communication and water systems.[6] Although prolonged outages cannot be entirely avoided, characterizing their distributional patterns and correlates can inform strategies that reduce their consequences and improve resilience.[7,8]

Louisiana consistently records some of the nation's longest outage durations.[9,10] Between 2013 and 2023, the average duration rose 76.4 percent, increasing from 5.5 to 9.7 hours, with the sharpest increase occurring between 2019 and 2020.[10] Prolonged outages are frequently associated with severe weather,[11,12] and the state's electric grid ranks among the least reliable nationally.[11,13] Although Louisiana Public Service Commission (LPSC) regulates utilities statewide,[14] service territories and ownership models vary by parish, producing a patchwork of operators, regulators, and service providers that add operational complexity to the restoration process. The institutional and network heterogeneity, coupled with rising demand,[13] highlight that statewide and utility level metrics do not fully account for how long outages last in specific communities. Parish level evidence on the correlates of outage duration remains limited in the public record, even though parishes exercise meaningful authorities over customer end point electrical codes.[15] The controlled load shed on April 26, 2025 in northwest Louisiana[16] illustrates the value of finer grained outage report documentation and accounting, since restoration timelines were reported at a regional scale without local-specific duration detail.[6]

Prior research on power outages has largely emphasized system-level reliability metrics or utility-wide restoration timelines, often linking outages to broad measures of weather severity. Many studies attribute the majority of outages, often 75% or more, to severe weather events,[17–20] and examine grid level reliability under these stressors.[21–23] Such studies have provided valuable insight into transmission line failures, distribution network resilience, and blackout mitigation.[18,22,24] However, they also tend to treat outages as binary outcomes or rely on national or state averages, masking local variation in the duration. County and parish level

studies that do exist often emphasize weather[3] or broad social vulnerability indicators,[5] rather than grid interpretable conditions at the customer endpoint.

This study addresses that gap by examining parish level associations with annual outage duration per household in Louisiana, expressed as a household level variant of the System Average Duration Index (h-SAIDI). Two weather measures were analyzed, severe weather damage and the frequency of events, to capture heterogeneity in local manifestation. To center analysis on the service interface of the distribution grid, three customer endpoint indicators were included for operational salience. The prevalence of mobile homes was used to operationalize household configuration and dispersed siting along radial laterals in rural areas. Mobile homes are the second most common housing structure and the proportion in Louisiana is over twice that of any other state.[25]. Mobile and manufactured homes may contain equipment not designed to withstand severe weather,[26] which could prolong outages. In addition, terrain challenges in rural areas can delay restoration with poles set in marshes and exposure of infrastructure to dense vegetation.[10] Lack of vehicle access captures physical mobility that may limit the ability to obtain alternate resources, maintain communications, or receive emergency services during extended outages.[27] Unemployment serves as a contextual indicator of daytime occupancy and potential patterns in electricity demand or outage reporting,[28] which could indirectly align with outage durations. This is pertinent as Louisiana residential customers use 46.3% more electricity than the average U.S. customer, and most electricity is used in air conditioning (36%), water heating (16%), and space heating (12%).[11] Using five years of outage data, normalized by the number of households, and matched with event-based weather records, the analysis identifies patterns of outage duration that cannot be explained by weather and grid alone.

The rest of the paper is summarized as follows. The next section outlines the data sources, variables, and statistical modelling techniques used to examine parish-level outage duration variation in Louisiana. The results section then summarizes parish level associations for severe weather damage and event frequency, and the three customer endpoint indicators. The discussion interprets the findings in the context of Louisiana service territories and ongoing resilience initiatives. The final section concludes the study with implications for future research.

METHODS

Data and variable construction

Power outage data was collected from the Event-correlated Outage Dataset In America, located at located at *https://catalog.data.gov/dataset/event-correlated-outage-dataset-in-america*. The dataset was published by Pacific Northwest National Laboratory (PNNL) and derived from the Environment for Analysis of Geo-Located Energy Information (EAGLE-I) Recorded Electricity Outages, located at *https://doi.org/10.6084/m9.figshare.24237376*. The EAGLE-I platform, maintained by Oak Ridge National Laboratory (ORNL), was developed to provide real-time outage information for emergency response, particularly for Department of Energy (DOE) and other government emergency responders.[29] Although not initially intended for retrospective data analysis, the archived EAGLE-I data have since been curated to support post hoc research into power outages and related topics.[30,31] Catahoula Parish was present in the EAGLE-I data, indicating that outages were recorded, however, no corresponding events were included in the merged dataset by PNNL. This suggests that either the recorded outages did not meet thresholds required for event classification or were excluded during event level aggregation. Catahoula was therefore excluded from analysis to preserve data integrity due to the absence of qualifying outage events.

The PNNL merged dataset organizes continuous outage reports into discrete events using thresholds for duration and customer count. Each outage event record includes a start time, duration (in hours), summary statistics describing the number of customers without power (min, max, and mean customers). For each parish-year, the customer outage hours were computed as the product of the outage duration (in hours) for each event and the mean number of customers affected. These values were then summed across all events for the parish year and divided by the total number of households in that parish, resulting in an annual estimate of outage duration per household. This metric is conceptually similar to the System Average Interruption Duration Index (SAIDI), a standard reliability indicator in distributed power systems.[32] According to IEEE Standard 1366, SAIDI represents the average total duration of sustained interruptions experienced per customer over a specified period, calculated as the sum of all customer interruption durations divided by the total number of customers served.[32] Although the IEEE standard differentiates between 'interruption' and 'outage', the term 'outage' is used in this work to remain consistent with the EAGLE-I source dataset, which reports power loss in terms of 'customers out'.[29] In this study, a household-level SAIDI analog was constructed by

summing the customer outage hours per parish-year and dividing by the number of households. Given that the majority of customers in Louisiana are residential (87%),[11] and that a 'customer' generally corresponds to a metered household account,[32] dividing by the number of households results an interpretable measure of annual outage duration per household.

Weather event data was collected from the National Centers for Environmental Information (NOAA) Storm Events Database, located at *https://www.ncdc.noaa.gov/stormevents/*, for the same years and locations as the outage data. The database contains significant weather events from January 1950 to April 2025 with enough intensity to cause disruption to commerce, property damage, injury, or loss of life.[33,34] Of the forty-eight possible event types, the Louisiana data contained eight (flash flood, flood, heat, lightning, strong wind, storm surge, and tornado), all associated with power outages in current research[1,12] and Louisiana state level reports.[11] Two variables were derived, the number of severe weather events per parish-year (count), and the total monetary damage (in billions USD), representing event severity. The weather damage variable was scaled in billions to improve interpretability and ensure numerical stability across predictors. This dual representation recognizes that some significant weather events exist without documented damage, and others are associated with unequal levels of damage.

These customer endpoint indicators were derived from the CDC/ATSDR Social Vulnerability Index,[35] which aggregates census-based metrics to assess resilience from disasters. The SVI has recently been used in correlation with power outage data[5,12,36,37] and is recommended for use with EAGLE-I archival data to investigate new outage associations. [38,39] The SVI captures preparedness and evacuation vulnerabilities, such as a lack of transportation or inflexible work schedules, which can hinder disaster preparation and response.[27] The years 2014, 2016, 2018, 2020, and 2022 were selected for analysis due to availability of complete parish-level data when merged with the NOAA and PNNL datasets.[35] Initially, apartment housing (number of units in buildings with 20 or more dwellings) was considered due to its potential to influence grid load concentration and restoration dynamics. However, this variable was excluded from the final model due to high correlation with other structural indicators and low feature importance, discussed in the next section.

The final dataset contained 310 observations for 63 parishes in the state of Louisiana across 5 years. The data was quantitative in nature except for the Parish name and year, which was qualitative. The outcome variable was annual outage hours per household (h-SAIDI), defined as the total number of customer outage-hours per year divided by the number of households in that parish. The covariates included severe weather damage, number of severe weather events, mobile home and unemployment prevalence, and lack of vehicle access. A summary of variable definitions and ranges is provided in **Table 1**.

Variable name	Definition and operationalization	Range and units
Annual outage duration per household (h-SAIDI)	Outcome variable; the total number of customer hours without power within a parish for that year (parish-year) divided by total number of households	0-672.150 (hours/household)
Severe weather damage	Sum of property damage from outage-related severe weather events, per parish-year	0-7.0, in billions USD (nominal)
Number of severe weather events	A count of severe weather events per parish-year (all available for Louisiana: flash flood, flood, heat, hurricane, lightning, strong wind, storm surge, and tornado) per parish-year	0-40, events/year (integer count)
Mobile homes	Number of mobile home units in a parish-year divided by the total households in the parish-year	0.005-0.732 (units/household)
Unemployed	Number of unemployed individuals (civilians age 16+) divided by the total number of households in the parish-year	0.008-0.105 (persons/household)
No vehicle access	Proportion of households without vehicle access in the parish-year	0.009-0.415 (proportion, 0-1)

Table 1. Operationalization of variables.

Data visualization

Prior to statistical modeling, patterns in the outcome variable were examined to better understand temporal. **Figure 1** shows parish level patterns in mean versus median annual outage duration (h-SAIDI), highlighting important differences in outage profiles across the state.

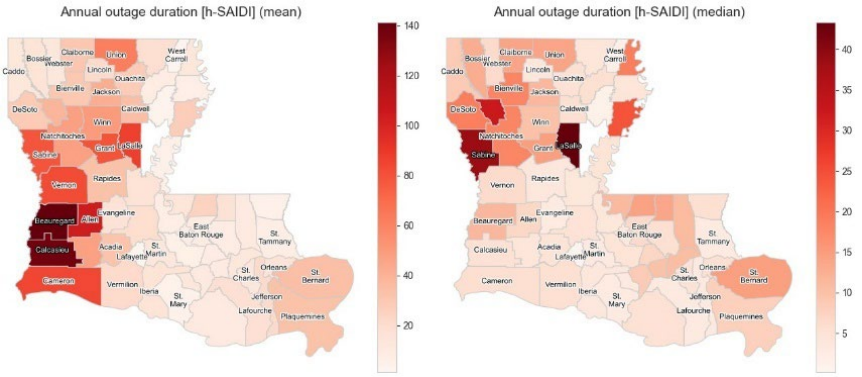

Figure 1. Mean (left) and median (right) annual outage duration per household (h-SAIDI) by parish.

In **Figure 1**, darker shading indicates higher values. Large mean-median gaps illuminate parishes where annual outage durations are driven by infrequent extreme events, whereas high values in both metrics indicate consistently prolonged outages across the year. Parishes such as Cameron, Allen, Calcasieu, Beauregard, and Vernon exhibit exceptionally large percentage gaps, indicating that infrequent but severe outage events dominate annual totals despite most outages being much shorter. In contrast, parishes with both high mean and median values, including LaSalle, Natchitoches, and Sabine, point to persistent reliability issues in which extended outages are common rather than exceptional. Quantifying these disparities helps distinguish areas where resilience strategies should focus on mitigating rare high impact events from those requiring systemic reliability improvements to reduce consistently long interruptions.

Building on the multi-year means and medians in **Figure 1**, the ten parishes with the highest mean values were further examined. **Figure 2** plots mean, median, and maximum annual outage hours per household (h-SAIDI) for the top ten parishes by maximum value, allowing a view of chronic outage prevalence versus acute spikes.

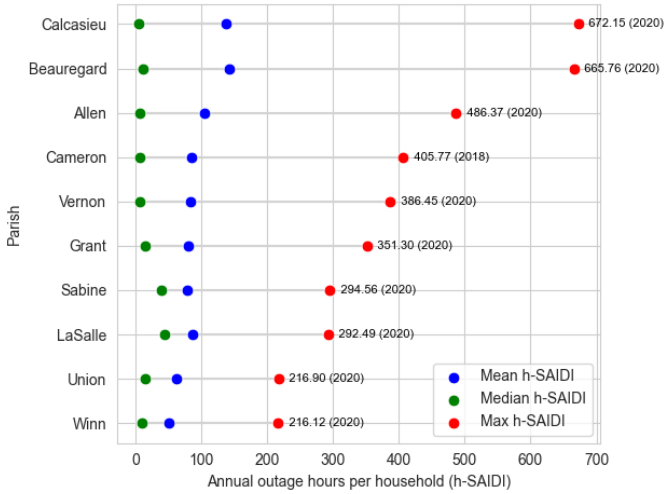

Figure 2. Comparison of mean, median, and maximum annual outage duration (h-SAIDI) for the top ten parishes with the largest single year values.

As seen in **Figure 2**, Central Louisiana parishes experience both acute outage events as well as high median and mean values. The maximum value is Calcasieu, meaning the average household in Calcasieu Parish experienced a total of 672 hours without power

in 2020, equivalent to approximately 28 days over the course of a year, aggregated across all events. Structural hotspots appear to be LaSalle, Sabine, Grant, Allen, And Beauregard, where there is an overlap of high mean, median, and max. **Figure 2** also shows that all except one of the extreme outage events occurred in 2020. The surge in 2020 aligns with an unprecedented sequence of severe weather events, including deadly tornadoes and several hurricanes. During the Easter tornado outbreak April 12-13, approximately 140 tornadoes caused 32 fatalities and over 250 injuries across ten states.[40] At least eight tornadoes affected northeast Louisiana on Easter Sunday, with approximately 458 homes damaged and 23 destroyed in Ouachita Parish. On August 27, Hurricane Laura made landfall in Cameron Parish as a Category 4 hurricane.[41] Hurricane Delta compounded the damage of Laura, followed by Zeta in southeastern Louisiana.[42] The cumulative impact of these disasters led to extensive grid disruption and prolonged power outages.

To further examine this pattern, a prominence-based peak detection filter (threshold ≥ 0.15) was applied to normalized customer outages in 2020. As shown in **Figure 3**, the most pronounced spikes occur in parishes such as Allen, Beauregard, and Calcasieu, reinforcing the severity of storm related disruption.

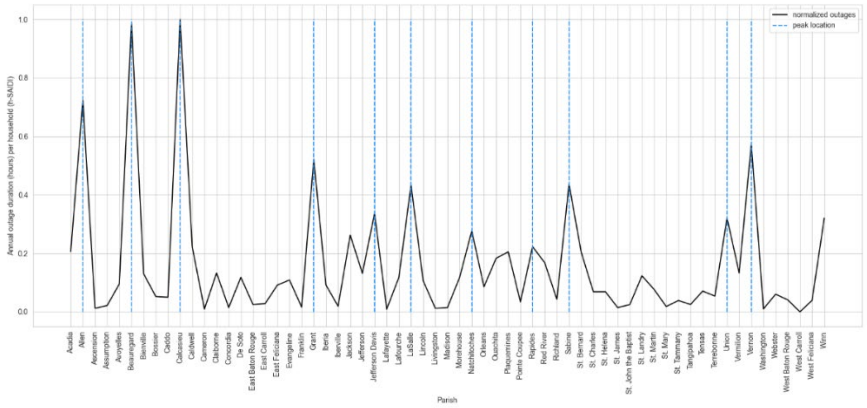

Figure 3. Customer outages per year with prominence filter = 0.1.

Interestingly, not all high-exposure areas exhibited elevated outage severity. As shown in **Figure 4**, Bossier Parish experienced the highest number of severe weather events in 2020 but reported few outages and minimal damage. This contrast suggests that outage duration reflects not only reflects severe weather damage or event frequency, but also by underlying system conditions and recovery capacity.

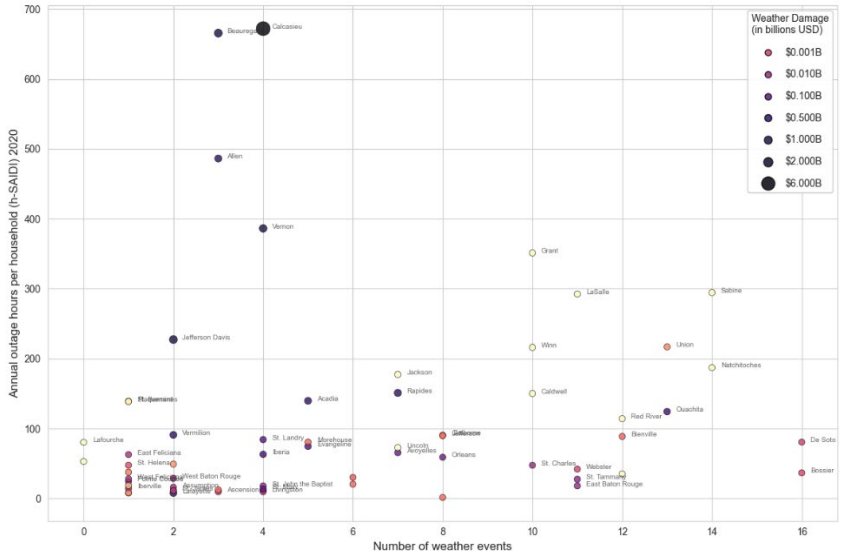

Figure 4. Annual outage hours per household vs number of weather events in 2020 (colored by damage).

Dimension reduction and descriptive statistics

All analyses were conducted in Python 3.12 using scikit-learn and `statsmodels` libraries unless otherwise specified. A Lasso regression regularization technique with standardized values was used to reduce dimensionality by identifying redundant or irrelevant features. This technique aligns well with linear regression models and penalizes less informative variables. The resulting feature weights ranked from highest to lowest were: weather damage (42.067), mobile homes (11.865), unemployed (-8.538), no vehicle (-7.898), number of weather events (7.773), and apartment (-3.415). Weather damage and mobile homes emerged as dominant linear features, while unemployed and no vehicle access were negatively associated with power outage burden. For robustness, a random forest regressor was used to compute permutation-based feature importances. As shown in **Figure 5**, the random forest confirmed weather damage as the most influential feature across both linear and nonlinear models, and suggested that the influence of mobile home prevalence was more linear than nonlinear in nature.

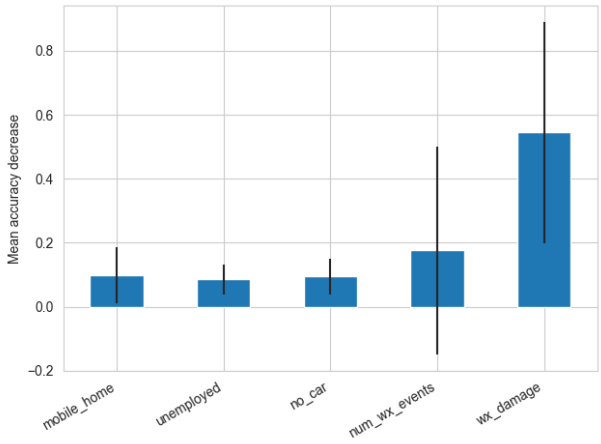

Figure 5. Permutation feature importances.

Table 2 displays descriptive statistics and Pearson correlation coefficients for the variables, including the dependent variable annual outage duration per household. As expected, the dependent variable showed strong correlation with weather damage, and significant correlations with other predictors. The independent variables were weakly correlated, with the exception of a modest negative association between no vehicle access and the number of weather events. To further evaluate predictor independence, a variance inflation factor (VIF) test was performed. The mean VIF for the model was 1.339, with the highest being 3.702 for the unemployment variable. All VIF values were well below the common threshold of ten, suggesting that multicollinearity was not a

concern.[43]

Variables	Mean	Std. Dev.	1	2	3	4	5	6
1 Annual outage duration per household (h-SAIDI)	29.453	76.619	1.00					
2 Mobile home	0.259	0.126	0.15**	1.00				
3 Unemployed	0.037	0.013	-0.15***	-0.09*	1.00			
4 No vehicle	0.141	0.120	-0.13**	-0.02	-0.11*	1.00		
5 Num weather events	4.784	5.531	0.10*	-0.03	-0.18***	0.05	1.00	
6 Weather damage	0.074	0.463	0.53***	-0.08	-0.04	-0.10*	0.01	1.00

Table 2. Descriptive statistics and Pearson correlation coefficients (n = 320). *p < 0.10; **p<0.05; ***p<0.01

The descriptive statistics indicate a right skew in the annual customer outage hours per household, with several parish-years exhibiting extreme values relative to the mean. This distribution reflects the cumulative nature of outage durations and the varying scale of service interruptions across Louisiana parishes over time.

While **Table 2** reports bivariate Pearson correlations, these measures do not account for interrelationships among the variables in the study. Several variables are moderately correlated, and examining them in isolation could obscure or inflate their apparent relationships with the outage duration per household. To address this, a generalized linear model (GLM) with a Gamma distribution and log link was estimated, appropriate for the positive, right-skewed distribution of annual outage duration per household. The GLM quantifies the statistical association of each variable with annual outage duration per household while adjusting for the others, providing partial association estimates that are robust to multicollinearity and more accurately reflect the complexity of the observed patterns.

RESULTS

The GLM was implemented with a Gamma distribution, log link, and heteroskedasticity-consistent (HC3) standard errors using Python version 3.12 and the `statsmodels` package version 0.14.1. Model estimation used iteratively reweighted least squares (IRLS), a standard maximum likelihood estimation technique for GLM that accounts for non-normally distributed outcomes and applies link functions to transform the expected value of the dependent variable. The Gamma-log specification models the logarithm of the expected outcome, enabling multiplicative interpretation of predictor effects while ensuring strictly positive predicted values. This modeling approach complements the correlation analysis by identifying which associations remain statistically significant in a multivariable structure and by estimating their relative magnitudes after adjusting for other variables in the model. **Table 3** presents the estimated coefficients, standard errors, and significance levels for each explanatory variable.

Variables	Coef.	Std. Error	z stat	p value
1 Intercept	2.916***	0.462	6.312	0.000
2 Mobile home	2.281**	0.851	2.680	0.007
3 Unemployed	-19.568*	8.255	-2.239	0.018
4 No vehicle	-2.329*	0.901	-2.208	0.010
5 Num weather events	0.068**	0.020	3.310	0.001
6 Weather damage	1.999***	0.233	9.179	0.000

Table 3. Summary of coefficients and significance levels from the GLM for annual outage duration per household in Louisiana. *p < 0.05; **p<0.01; ***p<0.001

The model achieved a Cox-Snell pseudo R^2 of 0.225, indicating moderate fit. McFadden's pseudo R^2 was 0.032, consistent with conservative fit statistics in Gamma GLMs with high-dispersion outcomes. The Pearson chi-squared statistic of 1070 with 304 degrees of freedom, resulting moderate dispersion with a factor of approximately 3.52. Robust standard errors were used to account for heteroskedasticity. Five high outage parishes (Allen, Orleans, Evangeline, and Jefferson parishes in 2020, Cameron parish in 2018) are largely responsible for the dispersion value. Allen parish in 2020 is the largest outlier, with observed outage hours greater than thirteen times higher than the fitted value. Attempts to fit a more flexible Tweedie GLM resulted in inferior model fit (Pearson chi-square value of 6100, lower log-likelihood), suggesting the Gamma distribution remained the best option for this dataset. Model interpretation thus focused on coefficients and directionality of effects.

As shown in **Table 3**, all predictors were statistically significant at the 0.05 level of significance. Weather damage and prevalence of mobile homes were the strongest predictors, corresponding to multiplicative increases in expected annual outage hours per household of approximately 7.38 times and 9.78 times, respectively. In a Gamma log model, each coefficient in the model represents the natural log of the multiplicative change in the expected value of outages per household for a one unit increase in that predictor, which makes the multiplicative factor e^{β}, therefore $e^{1.999} = 7.38$ and $e^{2.281} = 9.78$. Unemployment rate and proportions of households without vehicles were both negatively associated with outage rates. Each additional extreme weather event corresponded to an approximate 7.0% increase in expected annual outage hours per household ($e^{0.068} - 1$). .

DISCUSSION

Weather damage exhibited the largest positive association with annual outage duration per household (coef. = 1.99, $p < 0.001$), indicating that parishes experiencing greater financial loss from severe weather events also tended to experience longer cumulative outages. The number of severe weather events was also positive but substantially smaller in magnitude (coef. = 0.068, $p = 0.001$). Because coefficients are on the link scale of the Gamma GLM, magnitudes are not comparable across differently scaled covariates; the consistent result is that weather damage is more salient than the frequency of events. **Figure 6** shows the same pattern spatially and reveals a geographic contrast. The year 2020 was selected because it exhibits the largest aggregate weather damage and the widest cross-parish dispersion, maximizing contrast for assessing associations between severe weather and outage durations.

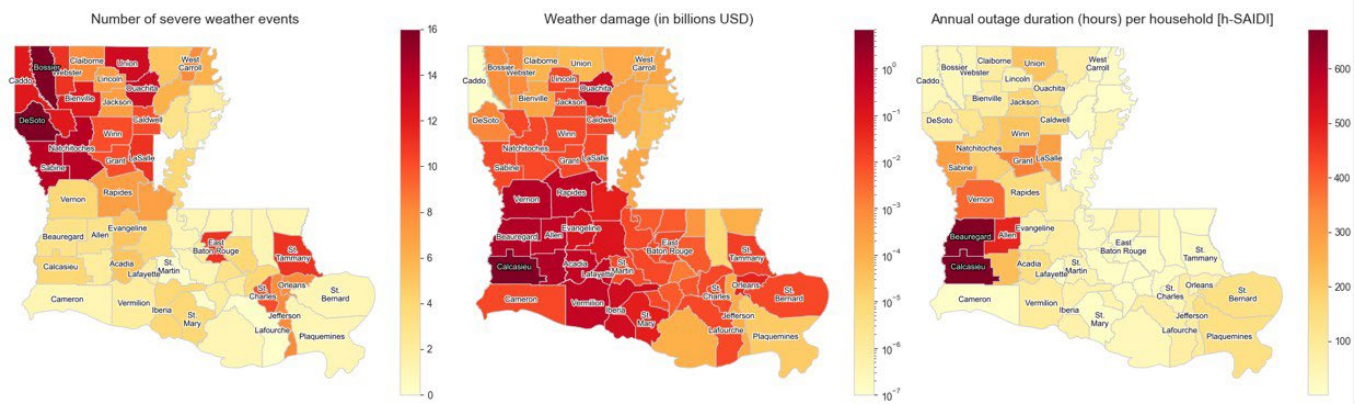

Figure 6. Severe weather factors associated with annual outage duration per household (h-SAIDI), 2020.

In **Figure 6**, high damage areas co-locate with elevated h-SAIDI, whereas high event counts alone do not imply long outages. In the northwest, for example, Bossier Parish records many events but comparatively low damage and short outage duration. That geography aligns with institutional anchors and recent resilience activity. For example, Barksdale Air Force Base's energy resilience efforts include reducing energy consumption, addressing waste, upgrading or replacing systems, retrofitting fixtures and controls, and implementing backups and redundancy.[44,45] Louisiana's new Hubs for Energy Resilient Energy Operations (HERO) is seeding additional capabilities (e.g., a deployable battery hub in Bossier City) alongside pilots in Baton Rouge, Lafayette, New Orleans, and elsewhere.[46] In the Baton Rouge-Lafayette corridor, Louisiana State University (LSU)-led efforts on resilience further situate those metros as nodes of planning and restoration capacity, which is consistent with locales in **Figure 6** that show damage but relatively modest h-SAIDI.[47]

The prevalence of mobile homes was the second largest positive association with annual outage duration in the model (coef. = 2.281, $p = 0.007$). Concentrations of mobile homes imply differences in grid service configuration and restoration logistics, including exposed connection points, and vegetation proximity,[10] which can increase the time required to restore power. In addition, mobile homes may not be readily accessible by interstate or public transportation, and clustered in communities, which may increase the number of households experiencing and reporting outages.[48] **Figure 7** shows an overlay of mobile home prevalence with the contemporaneous outage hours per household (h-SAIDI). The year 2020 is retained for temporal

correspondence with **Figure 6**, since mobile home prevalence varies little across years, and parish means and medians show a similar pattern.

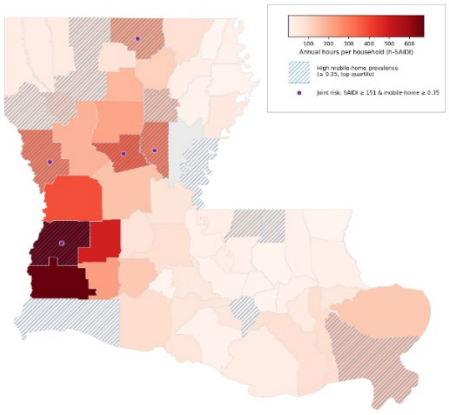

Figure 7. Annual outage duration (h-SAIDI) and mobile home prevalence in Louisiana parishes, 2020.

Figure 7 shows a clear concentration of higher annual outage hours per household in a west-central and southwest corridor, including Calcasieu, Cameron, Beauregard, Allen, and Vernon, with adjacent parishes also elevated. The striped overlay marks parishes in the upper quartile of mobile-home share, and the purple markers identify those in which both outage duration is high and mobile home share meets the threshold indicated in the legend. Jointly elevated parishes form a defensible priority set for reliability improvements and response and restoration investments. These could include hardening feeder lines, sectionalizing and switching, vegetation management, subsidizing repairs and mobile home upgrades and assisting communities with resources such as generators.[49]

The negative association of unemployment with annual outage duration (coef. = -19.56, p = 0.018) was unexpected. One possible explanation is that it is attributable to network design and restoration logistics rather than household occupancy. Five year median maps show higher unemployment concentrated along the Interstate-10 and Mississippi corridor and adjacent urbanized parishes where more dense service areas exist (**Figure 8**). Restoration may proceed faster where distribution feeders are shorter, redundancy is greater, and repairs restore service to more customers per action.[5,50] Rural cooperative territories, by contrast, rely on long radial systems through difficult terrain, and comparable work restores fewer households and prolongs duration.

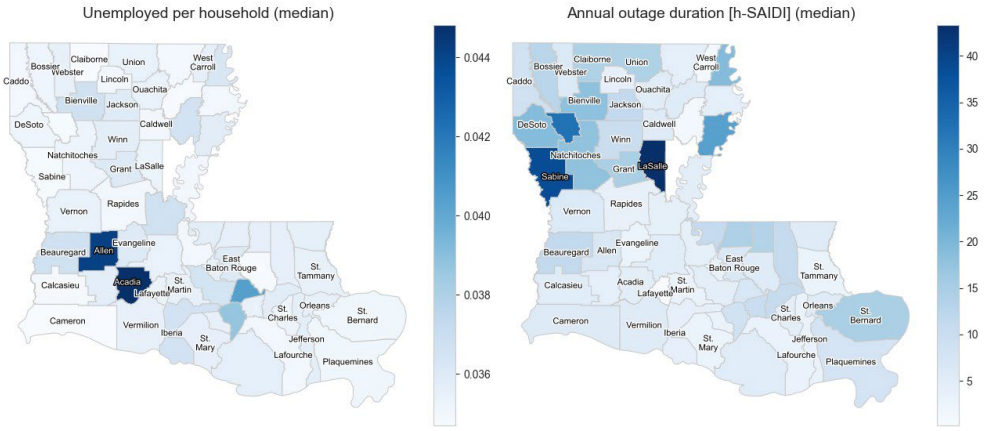

Figure 8. Five year median comparison of unemployed and annual outage duration per parish.

Two descriptive checks support this interpretation. First, a cross-sectional plot of parish medians shows a weak negative correlation between unemployment and the annual outage duration per household (**Figure 9a**; r = -0.11). Second,

stratifying by utility company class[51] and comparing with a Mann-Whitney U test shows substantially higher median annual outage hours in cooperative territories than those that are investor owned (**Figure 9b**).

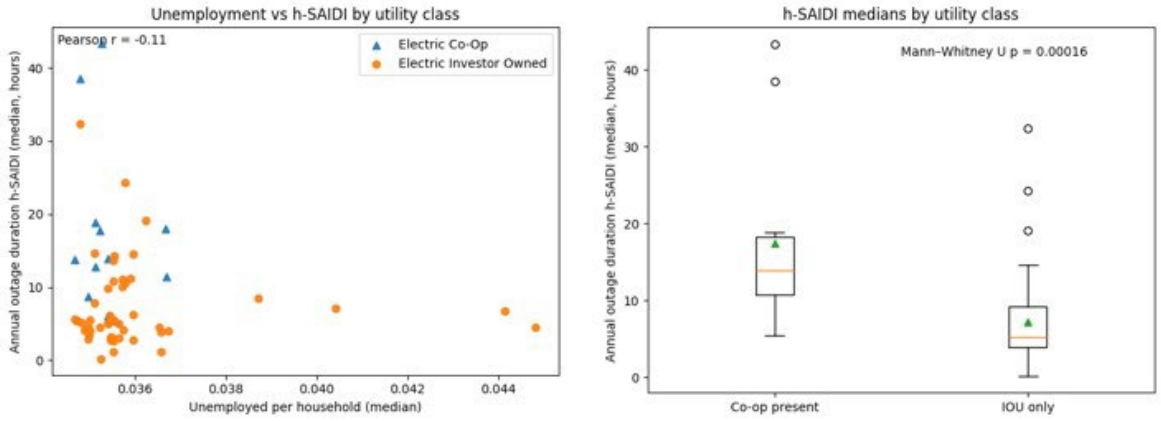

Figure 9. (a) Cross-sectional correlation of unemployment vs h-SAIDI (medians), coded by utility class; (b) Annual outage duration (h-SAIDI) medians by utility class.

For further testing, the unemployed variable was decomposed into a between-parish component and a within-parish component (annual deviation from the median). The within-parish plot of Δunemployed and Δh-SAIDI and a locally weighted scatterplot (LOWESS) smoothing function[52] (**Figure 10a**) exhibits only a shallow downward trend. Stratifying by weather damage tertiles produces similarly weak gradients (**Figure 10b**). Taken together, the checks suggests that unemployment functions as a contextual proxy for utility operational network characteristics rather than household daytime occupancy.

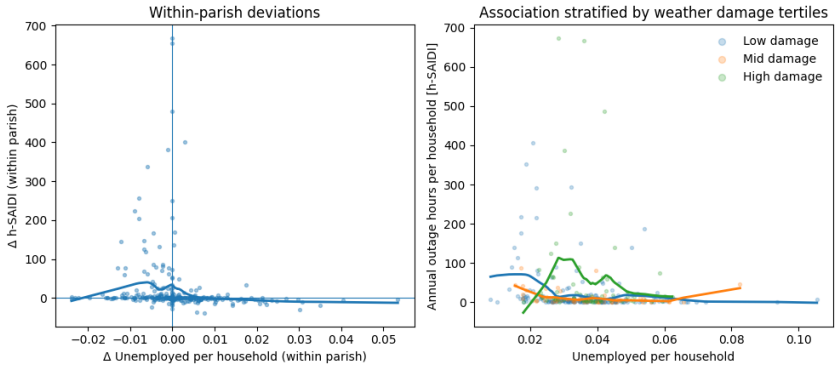

Figure 10. (a) Within parish deviations after subtracting the mean (2014-2022); (b) Stratified association by weather damage.

Similarly, the results showed negative association with lack of vehicle access (coef. = -2.32, p = 0.010). This could also be explained by concentrations of carless households in urban areas[48] where grid topology and operations favor faster restoration. A violin plot of medians with 95% bootstrap percentile confidence intervals (B=3000 resamples) shows a marked increase in the proportion of households without a vehicle in 2022 (**Figure 11**).

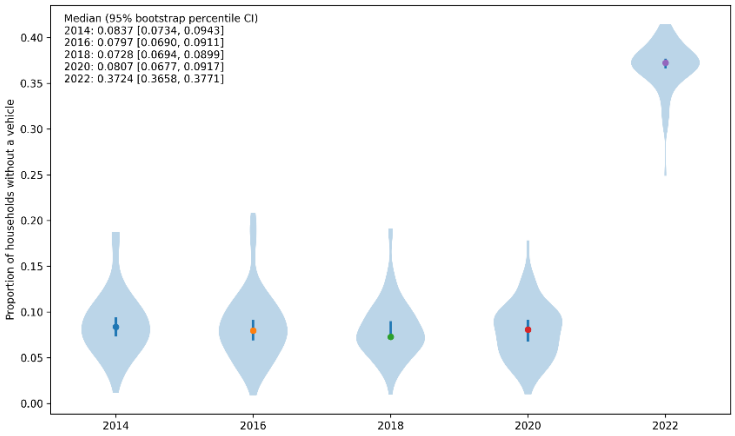

Figure 11. Violin plot by year with medians and 95% bootstrap percentile confidence intervals.

The medians of the parish distributions in **Figure 11** for 2014-2022 were 0.0837, 0.0797, 0.0728, and 0.0807, and 0.03724, respectively. Across years, distributions differ significantly by a Kruskal-Wallis H test (H=151.12, *df*=4, *n*=310, $p = 1.17 \times 10^{-31}$) with a large effect size $\varepsilon^2 = 0.482$.[53] The 2022 median is 0.0373 [0.365, 0.377], whereas 2014-2020 medians cluster near 0.08, indicating a substantial left shift in the cross section. The apparent 2022 divergence may reflect compounding factors between 2020 and 2022, including pandemic-era economic dislocation, changes in household composition, and recovery dynamics following the severe 2021 hurricane season. Weather damage, displacement, and relocation into denser housing, often in urban areas with lower vehicle ownership, could have shifted parish level rates upward. Importantly, this shift does not alter the association with outage duration; rather, it reinforces that no vehicle access likely proxies distribution network density and restoration dynamics, instead of household mobility.

Overall, the results show that severe weather and customer endpoint conditions jointly structure outage duration at local scale. The strongest positive association of severe weather damage with outage duration is consistent with reliability theory, where restoration time reflects actual failure, not a count of events.[54] This explains cases like parishes with many events but low damage that do not experience long durations. The customer endpoint conditions at the household level add explanatory power beyond severe weather. Mobile homes emerge as the second largest correlate, which supports a distribution edge perspective of slower restoration times with longer feeders and slower sectionalized restoration. The negative associations for no vehicle access and unemployment are consistent with spatial concentration of these indicators in urbanized service territories characterized by shorter spans, higher meshing, and switching operations reduce duration.

CONCLUSIONS

This study examined parish-level outage duration per household in Louisiana by integrating event correlated outage records, severe weather measures, and customer endpoint indicators across 63 Louisiana parishes from 2014 to 2022. Outage durations were not uniformly distributed, even among parishes with similar counts of severe weather events, indicating substantive local variation consistent with difference in distribution network characteristics and conditions at the service interface. A Gamma regression model with a log link and robust errors was used to estimate associations, complemented by spatial and distributional summaries and nonparametric checks. Damage from severe weather was identified as the strongest positive correlate of the household level outage duration, while event frequency was not consistently aligned with duration. The prevalence of mobile homes was positively associated with outage duration; unemployment and lack of vehicle access were negatively associated, consistent with the operational advantages of robust distribution networks.[55]

This study findings contribute to ongoing grid resilience efforts by indicating where targeted actions are likely to reduce long durations. High priority areas are those where severe weather damage and mobile home prevalence coincide along long radial feeders; actions include added sectionalizing and reclosers, vegetation management, and conductor and pole upgrades, with selective consideration of microgrids. In regions with high unemployment or limited vehicle access, complementary strategies include pre-positioned backup power sources, walkable access to relief sites, and shared service centers with refrigeration or

charging capabilities. Standardized sub-parish outage reporting would improve accounting that supports resilience investment decisions Future work should incorporate operational utility data such as feeder topology, switching and outage management logs, vegetation cycles, and asset age, extend analysis to sub-parish circuits and event level timelines, compare provider classes, and evaluate targeted interventions longitudinally.

DISCLAIMER STATEMENT

The views expressed in this document are those of the authors and do not reflect the official policy of the U.S. Naval Academy, Department of the Navy, the Department of Defense, or the U.S. Government

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PRESS SUMMARY

Power outages are lasting longer and occurring more frequently across the United States, raising concerns about the reliability of regional energy systems. While previous studies have focused on severe weather and overall grid performance, few have examined how customer endpoint conditions shape outage duration at the distribution edge. This study analyzed data from 63 parishes in Louisiana and found that severe weather damage and prevalence of mobile homes were strongly associated with of higher outage duration, whereas unemployment and limited vehicle access showed negative associations. These findings highlight the importance of planning for resilience by accounting for both severe weather and localized customer endpoint conditions.

Leveraging Hybridity: Alfonso Ortiz as Native American, Activist, and Anthropologist

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ABSTRACT
Two major efforts by Indigenous scholars include advocating for Indigenous sovereignty and theorizing relation-building with non-Indigenous people. As attempts are made to indigenize the academy, can inspiration be drawn from past Indigenous scholars who were ahead of their time in a dual commitment to both goals? This paper focuses on Alfonso Ortiz, a former Native American scholar, activist, and anthropologist. Exploring his archival collection, held at Princeton University, lends insight into his hybrid positionality in higher education. Seeking to unravel the way Ortiz mediates between institutions, epistemologies, and people, a thematic analysis of archival materials unravels three forms of hybridity: Native-educational, institutional-activist, and anthropologist-activist. Ortiz's case shows that hybridity is not a roadblock to Native American priorities; on the contrary, hybridity provides tools for agentive action carried out on behalf of Native American communities. More importantly, the implications of each form of hybridity raise new questions for non-Indigenous institutions and individuals, which may need to rethink their purposes as they are called into relation with Indigenous students, faculty, and communities.

KEYWORDS
Indigeneity; Hybridity; Alfonso Ortiz; Relationality; Sovereignty; Native American Studies; Archival Analysis; Agency

INTRODUCTION

What does it mean to indigenize higher education? Any answer to this question must begin by recognizing the broader settler colonial context faced by Indigenous peoples. Patrick Wolfe describes settler colonialism as involving a persistent attempt by settlers to eradicate and replace Indigenous peoples from a particular territory.[1] Assimilation is a key tool used to achieve the settler colonial vision; in the United States context, assimilation has involved the forcible, violent incorporation of Native Americans into the nation state through mechanisms such as boarding schools.[1] More recently, in the higher educational context, assimilation entails the inclusion but continued domination of Indigenous epistemologies and values by Western universities. For Devon Mihesuah and Angela Wilson, this is a particularly insidious issue as "the academy has much invested in maintaining control over who defines knowledge, who has access to knowledge, and who produces knowledge."[2] Likewise, observing that "academic institutions create the attitudes and beliefs that sustain imperial relations," Taiaiake Alfred highlights the urgency of scrutinizing the epistemological commitments of higher education.[3]

Indigenous sovereignty confronts assimilation and the larger eliminatory goal of settler colonialism; although it can be defined in many ways, one definition is the "self-governance or the right of [I]ndigenous peoples to maintain their unique forms of social, political, and cultural integrity."[4] For Elizabeth Cook-Lynn, indigenizing higher education means re-centering this goal of Indigenous sovereignty in Native American Studies (NAS) programs;[5] for others, such

as Mihesuah and Wilson, the indigenizing movement must assert Indigenous sovereignty across academia more broadly, addressing many issues and contexts such as the relationship between Native students' knowledge and Western academic knowledge or the institutional privileging of Western epistemologies by the university.[2] In supporting Indigenous sovereignty, the goal is not to subsume Indigenous knowledges into Western institutions in the name of "diversity," but to elevate Indigenous epistemologies to co-equal status and center Native voices in the academy. Kim TallBear writes about the incompatibility of Indigenous "incorporation *into* a (liberal) settler worldview"[6] further explained by Bryan Brayboy, who notes that Indigenous peoples embody both racial *and* political identities.[7] Indigenizing education must therefore focus less on inclusive multiculturalism—which may be useful for empowering racial, but not political minorities—and more on Indigenous autonomy. Moreover, those interested in indigenizing education must be wary of critical theory intending to empower people by gender ("whitestream" feminism) or class (Marxism), which Sandy Grande describes in *Red Pedagogy*.[8] These theories oppose Indigenous sovereignty on multiple grounds: first by advocating incorporation into a democratic settler state, and second by consigning Indigenous cosmologies to a primitive and necessarily past stage of human development.[9]

Yet, many of the same Indigenous scholars who advocate Indigenous sovereignty also acknowledge the need for relationality with non-Indigenous people. For example, rather than incorporating Native peoples into the nation-state, TallBear proposes "making kin," so that Indigenous peoples "can call non-Indigenous people ... to be more accountable to Indigenous lifeways."[10] Grande thinks about Indigenous to non-Indigenous relationality by hoping to "situate groups in relation (not in binary opposition) to each other, thereby avoiding ... the subsequent impulse to act or behave oppositionally."[11] Binary discursive distinctions between Indigenous and non-Indigenous peoples, such as "us" versus "them," are particularly damaging, Sharilyn Calliou points out, for perpetuating settler colonial cosmologies.[12] In the higher education context, what does it mean to advocate Indigenous sovereignty while also relating to or—as will be more directly explored here—coming into contact with non-Indigenous institutions, epistemologies, and people?

I am interested in analyzing this contact across three different contexts. First is the non-urban Native community context, from which thousands of Native American youth can be estimated to leave to attend American higher educational institutions.[13, 14] What is the relevance of Western ways of knowing to a Native community? Does Western knowledge have to replace Indigenous knowledge, as in many English as a Second Language models? Are past understandings lost in the acquisition of new content? Or might Native communities take advantage of Western knowledge to better understand the social power dynamics that they face? Second, there is the context of the Western institution, which is important as there are approximately 3,300 Native American faculty employed by American universities.[15] How does an Indigenous scholar navigate the demands of their employer while remaining committed to Native interests? Are there ways that the Western institutional platform may be used for Indigenous activist ends? Finally, there is the classroom context. Can disciplines known to have historical ties to colonialism be used for Native American activism?[16] What is the role of NAS programs primarily serving non-Native American students, such as the American Indian Studies major at South Dakota State University reported to be "almost 90 percent white"[17] or the Native American and Indigenous Studies Initiative at Princeton University, where only two percent of the entire student body self-reports as Native American, Native Alaskan, Native Hawaiian, or Pacific Islander?[18] Can non-Native students be taught about epistemic violence, a phenomenon that disparages Native students' ways of knowing?[19] Literature has explored how to indigenize the classroom for Indigenous students,[20–22] but little work has examined how Indigenous teachers can effectively challenge non-Indigenous students about their epistemologies. And for the many non-Native instructors teaching Native Studies topics, it is also worth considering what sort of relations they might foster between Native Studies content and non-Native students.

To answer these questions about contact across the three different contexts, I explore the archival materials of Alfonso Ortiz, whose career was defined by his hybridity, serving at once as an anthropologist, Native activist, professor, and member of the San Juan Pueblo. A member of Princeton University's Department of Anthropology from 1967 to 1974, Ortiz advocated for the recruitment of Native American students and was chairman of the First Convocation

of Native American Scholars (henceforth "Convocation"), held on the Princeton campus in 1970.[23] He authored *The Tewa World* (1969), *New Perspectives on the Pueblos* (1972), and edited *Handbook of North American Indians*; among the many titles he held include President of the Association on American Indian Affairs, member of the Newberry Library Advisory Council, and consultant to the National Endowment of the Humanities.[24] Before Princeton, he taught at the Claremont Colleges for a year; in 1974, he moved from Princeton to the University of New Mexico (UNM), where he remained until his death in 1997.[25] He described himself as a "cultural anthropologist of structural persuasion," teaching symbolic and structural theory courses as well as courses on Native Americans and their related stereotypes.[26]

In my analysis, I use 'hybridity' to describe the quality of multiple positionalities or an engagement with multiple spheres. In his speech to the American Anthropological Association's 1970 session titled "Anthropology and the American Indian," Ortiz does not use the word 'hybridity,' but he does speak about his multiple affiliations as activist and anthropologist: "I have taken a position in the middle, fully aware of the dangers of being shot at from both sides."[27] My use of the hybridity concept draws on Kirin Narayan's perspective that an anthropologist is part of both a research culture and daily culture,[28] and Lila Abu-Lughod's presentation of her personal hybridity as anthropologist, reflecting on the process of pregnancy in Egypt and the United States.[29] Hybridity is also used by anthropologist Néstor García Canclini; he studies "the abrupt opposition between the traditional and the modern" in Latin American societies and the cultural formations that emerge from it.[30] Notably, some scholars outside of anthropology have discussed the concept of "two-eyed seeing," that is, "learning to see from one eye with the strengths of Indigenous ways of knowing and from the other eye with the strengths of Western ways of knowing."[31] While aspects of two-eyed seeing are certainly relevant to Ortiz's life, hybridity allows this project to remain grounded in Ortiz's agency, not just his knowledge. In other words, the object of analysis in this paper is not so much what Ortiz can know as it is what he can do.

In reading Ortiz's archival materials, it is clear that his hybridity allows him to interface with Western interests, relations, and epistemologies without assimilating into them. I show how hybridity can be leveraged to empower, rather than attenuate, efforts towards indigenizing higher education in the Native community, Western institutional, and classroom contexts.

METHODS AND PROCEDURES

The Alfonso Ortiz Papers (AOP) is a set of over 80 boxes containing research notes, correspondence, newspaper clippings, reports, and teaching materials housed at the Princeton University Library's Special Collections. The current research began with my exploration of archival materials specifically related to Ortiz's involvement with the Convocation, as part of the Princeton Department of Anthropology's attempt to recover its own history for its 50th anniversary celebration. At the same time, I brought a personal interest in the anthropology of education. This subfield of anthropology appraises the cultural dimensions of education in a broad sense, so the focus is not only youth in traditional schools but also, for example, members of civic engagement programs and faculty at colleges or universities.[32, 33] Participant observation dominates as the primary methodology for educational anthropologists, and I believed that the AOP was a ripe opportunity to inject archival insights to the field.

I ultimately completed a first pass through all 83 AOP boxes. During this stage, I noted any folders containing materials relevant to Ortiz's teaching, perspectives on Native American Studies, or the Convocation (held at Princeton). In a second pass, I put aside any of the noted folders containing materials without Ortiz's (or his students') own words. The remaining 59 folders constituted the corpus of materials analyzed for the project.

In the second pass, I took "fieldnotes" of the contents in the corpus folders. On the one hand, this process involved distilling what Elsie Rockwell calls "the material culture, graphic representations, and sensory and emotional milieu of schools" in the syllabi, lecture notes, Convocation correspondence, and other materials.[34] What sort of epistemic work was visible in the materiality of the AOP? What were the affective dimensions of Ortiz's work embodied in the archive? On the other hand, this work moved beyond analyzing individual document properties, instead following

the suggested methods of John and Jean Comaroff and, later, Hervé Varenne, synthesizing interconnections to distill themes from the corpus as a whole and the context constructing it.[35, 36] Following the second pass, I analyzed my fieldnotes alongside select digital scans of the corpus materials. Taking events described in documents as "ethnographic scenes," this was the point when I began organizing materials thematically given the insight they provided about hybridity. When necessary, I revisited the materials for a third pass.

Throughout the planning, archival analysis, and writing of this research, I often reflected on my positionality as a non-Indigenous researcher. As an Asian American, I have had firsthand experience with issues of race in the United States, and having grown up in Honolulu, I am familiar with aspects of Native Hawaiian history and cultural context. These experiences support my ability to empathize with Indigenous communities. However, I acknowledge that the Native Hawaiian context cannot be read metonymically for Indigenous communities writ large, and that Asian Americans occupy a position in Hawai'i that has relied upon settler colonialism.[37] Linda Tuhiwai Smith says that Indigenous people want "to determine priorities, to bring to the centre those issues of [their] own choosing, and to discuss them amongst [themselves]."[38] In light of this view, I entered the research process affirming that my work be in dialogue with—rather than privileged above—existing Indigenous scholars' perspectives. My goal here as a non-Indigenous researcher is to focus on the exploratory nature of the project, and I highlight themes emerging from Ortiz's work that may inform how to better serve Indigenous communities as well as non-Indigenous students. Recognizing that certain themes may have struck me particularly due to my positionality, such as those that resonated with my previous understanding of Native Hawaiian history or experience in education as an Asian American, I ground my discussion below in Ortiz's words as much as possible to leave room for additional insights emerging from a reader's own interpretation. At the end, I synthesize my results but consider the goal of this paper to be an impetus for further discussion.

A note about terms: I use 'Indigenous' in relation to broader discussions of indigenizing the academy and Indigenous peoples' common goal of sovereignty. I also use 'Native' to describe Indigenous peoples and contexts—not only in America, or else I say 'Native American'—including Ortiz's context. I only use 'Indian' when quoting Ortiz from his archival materials.

RESULTS AND DISCUSSION

The Native context

A key issue for Native youth at Western universities is the question of their pre-existing Indigenous knowledge. Ray Barnhardt and Oscar Kawagley write that "Native people may need to understand Western society, but not at the expense of what they already know and the way they have come to know it."[39] How can Ortiz's work inform how Native youth come into relation with Western institutions and remain committed to Native knowledges and priorities?

In this section, I draw upon Ortiz's typewritten notes that read as an outline for a speech to Pueblo youth.[40] This ethnographic scene is complemented by Ortiz's perspectives voiced in three other materials: a transcript of a panel discussion at the University of California at Los Angeles (UCLA) to consider a master's degree program in Native American Studies,[41] a set of questions for the steering committee of the Convocation,[42] and a letter to a Native elder.[43] Simultaneously a Tewa community member and Western educated scholar, Ortiz has what I call "Native-educational hybridity." Taken together, the materials in this section show his confidence in this hybridity as a productive tool for Native American communities. I begin by briefly discussing Ortiz's own Native-educational hybridity before turning to his conceptualization of this form of hybridity, presented in his advocacy of it to Pueblo youth.

Ortiz was born to a Hispanic mother and Tewa father but was raised primarily by his grandmother, Saya, in Ohkay Owingeh Pueblo, then known by the colonial name 'San Juan Pueblo.'[44] Ortiz left his Pueblo to pursue a bachelor's degree in sociology at the University of New Mexico (obtained in 1961), and later, a master's degree (obtained in 1963) and doctorate (obtained in 1967) in anthropology at the University of Chicago.[45] Bryan Brayboy describes the concept of transformational resistance as "the acquisition of credentials and skills for the empowerment and liberation

of American Indian communities."[46] In many ways, Ortiz's educational and career trajectory is an example of Brayboy's concept par excellence: via exposure to resources and the credentialism of Western educational institutions, Ortiz was empowered to serve his Pueblo (or perhaps Native American groups of the Southwest more broadly, through eventual scholarship and activist efforts). To be sure, the Native community is not only where Ortiz spent his childhood, but a place with which he maintained strong connections and to which he returned frequently. These connections are evident in the letter he writes while considering a position at Stanford, as he describes the "strongly-expressed wish of New Mexico Indian leaders that I be right here at hand in order to continue our mutual involvement in several projects."[47] Reflecting on his return from the East Coast to New Mexico, he describes it as his family's "13-year-old wish" finally fulfilled in 1974.[24]

In his speech to Pueblo youth, Ortiz advocates Native-educational hybridity, saying, "You owe it to yourselves and to your people, if you have special talents, to develop these talents to the highest degree so tha[t] you can put them to use on behalf of your people."[40] Such advocacy resonates with the writing of Vine Deloria Jr. on "new Indians" who face pressures from the academy to disengage from their communities while their communities simultaneously expect maintained engagement.[48] Deloria challenges young Native scholars to push back against these pressures from the academy and to remain connected to Native communities.[48] Likewise, Ortiz believes the youth have a responsibility to Pueblo members in not only horizontal (contemporary) relations, but vertical (generational) relations, too. In the speech, he ponders the question: "What is the ultimate value of a man's life?" He says that the youth are "links—the latest links—in an unbroken chain which stretches back in time for thousands of years" and asks listeners to reject any thought that "history began on the day [they] were born."[40]

Further rejection of individualism in Native-educational hybridity appears in the UCLA panel transcript. Ortiz is concerned that a potential master's program might be used as an "identity certification ... for Indian students whose identity crisis hit a little late."[41] An advocate of a longer, more rigorous doctoral program, he fears that the master's degree "can be a way of or used as an excuse for some urban-born and raised Indian students to use as a chan[c]e to affirm their ties and find their ways back to their communities ... hence [it] is an identity certification process ... which may not have much of an enduring impact on the quality of Indian existence now and in the future."[41] Whereas Ortiz encourages Pueblo Natives' educational attainment rooted in Pueblo identity and goals of service, he sees the potential master's degree credentialism of urban Natives as superficial and unsustainable. I recognize that Ortiz's comments here may be disparaging towards displaced Natives. One way of understanding Ortiz's words is through the lens of lateral violence, which involves "intra-racial abuse" amongst members of historically oppressed populations, such as Indigenous groups.[49] Crucially, lateral violence is produced by a combination of factors, including ongoing identity work in a settler colonial situation and disappearing traditional epistemologies.[50] This tie to broader structural violence is important to avoid painting Ortiz as intentionally harmful, even if his comments are damaging. Moreover, having acknowledged that lateral violence is at play, I still wish to emphasize Ortiz's point about rootedness in communal rationalities. To Ortiz, a university education is valuable for the potential benefit to the Native community, not the individual degree-seeking student. This observation underlines how Native-educational hybridity prioritizes rather than weakens collective Indigenous goals, and a similar finding about rationalities surfaces in the other two hybridity contexts.

As tools, educational credentials are not replacements for Native community wisdom. Ortiz makes this clear in his letter to friend Rolling Thunder, whom he asks to speak to his students in a letter: "They need to know of traditional wisdom such as that which speaks through you, to help guide their lives in better directions than they understand now. I know of such wisdom but do not have it myself as [of] yet."[43] Despite his possession of a doctorate, Ortiz feels lacking in traditional Native wisdom, something reinforced by another comment he makes in his speech outline. To Ortiz, Native elders do not have the same credentials supplied by Western academic institutions, yet they have credentials "in how to be Indian," which he respects because the elders "carry the knowledge of many thousands of years."[40] Similarly, Western higher education is not, by itself, a solution to Native issues, according to the archival documents. Writing about emergent higher education Native leadership programs, Ortiz says, "Leadership is already there in all Indian

communities ... [but community members] must have the opportunity to develop certain managerial-technical skills to understand and interpret the complex maze of federal programs now hitting them from all sides."[42] Western educational credentials, Ortiz implies, are valuable for their use with concrete purposes; in his speech, Ortiz believes that the uneducated "will not know how to defend our ways against enemies they do not understand."[40] Of course, without a grasp of what "our ways" are, a Western-educated individual has nothing to defend; this echoes Brayboy's conceptualization of Natives' "knowledge of survival" being a combination of both academic (Western institutional) and Native cultural knowledges.[51]

In sum, Ortiz believes that Native-educational hybridity is not counterproductive to Native American goals; on the contrary, he finds it a productive tool to be leveraged, so long as the 'Native' dimension is the impetus for engaging with Western educational institutions. As scholars such as Bryan Brayboy, Jessica Solyom, and Angelina Castagno call on institutions "to rethink ... what it means to be responsible to and for Indigenous peoples,"[52] it is important for universities to think of Indigenous students not simply as enrolled pupils but as community representatives with the potential to use their educational credentials for tribal empowerment. At the University of New Mexico, for example, Native American Studies programs have offered Native American students "the learning channels for directing their education and applying their knowledge in community-centered ways."[53]

The institutional context

Deloria says that in his day, close to the time Ortiz was at Princeton, "we were not recruited as scholars but as high-profile Indians."[54] Hiring policies have evolved since the period Deloria describes, but many of the questions applicable to Ortiz's situation at Princeton remain pertinent today: How can Indigenous scholars remain committed to Indigenous—rather than Western—priorities when employed in Western institutional contexts? Are all hopes of activism undermined by Indigenous faculty members' relations with their employing institution, or can a job at a Western university and potent Indigenous activism coexist?

During Ortiz's tenure at Princeton, he held simultaneous Princeton and Native American activist affiliations, which resulted in what I term "institutional-activist hybridity." This hybridity is clearly visible in the planning of the First Convocation of Native American Scholars, so the archival materials analyzed here revolve around that scene. The event itself took place on the Princeton campus between March 23rd and 26th, 1970, bringing what a press release says were "192 of this nation's outstanding leaders in education, the sciences, the arts, and humanities."[55] I begin by analyzing how Ortiz's institutional-activist hybridity manifests before turning to the generative capacities of this hybridity.

As a member of the Princeton community, there is a clear tension between Ortiz's activist stance and his responsibility to the university. In the "Call for a Convocation," he asks Native American scholars to be the ones who "take the lead in formulating clear-cut stands and goals."[56] In the absence of Native American students at Princeton, he expresses his thoughts in a letter to a man interested in the Convocation: "I started agitating on this front almost as soon as my feet touched the ground here more than two years ago ... when we get applications, you may be made to feel sure that I will be breathing hot and heavy over the shoulders of the admissions officers."[57] At the same time, though, throughout the planning of the Convocation, he serves as a primary liaison for Princeton to the American Indian Historical Society (AIHS) planning the event. He emphasizes to steering committee members the need for obedience to Princeton's expectations, saying, for instance, that accommodating twelve members of the Princeton community "is not a request; it is a statement of fact because this is the way the University operates."[58] After the conclusion of the Convocation, despite his fellow activist and president of the AIHS Rupert Costo's criticisms of Princeton personnel disrespecting Native American agency and commandeering the event,[59] Ortiz remains at the university until his departure for the University of New Mexico in 1974.

Ortiz's simultaneous positionality as Princeton professor and Native American activist can be read as an accommodation that benefits Ortiz, to use Stephanie Masta's concept.[60] Initially deploying the term to describe "the decision to

adopt some practices or values for the benefit it provides the [Native] student,"[61] Masta gives varied examples of accommodation used by Native students in a predominantly white school. These include actively identifying as Native, demonstrating affability to white peers, and falsifying information to white peers when teased.[60] In Ortiz's case, the notion of accommodation is not applied to a student, but rather a Native American scholar. Indeed, in correspondence with Rupert Costo, Ortiz stresses identification with Princeton and the beneficial security provided to him by the university: "My contribution as well as that of the others here must be seen as a Princeton contribution ... Princeton pays all of my bills, and when all is said and done I have to account for my existence here."[62]

Although affirming his responsibility to Princeton could, on the one hand, be read as submission to institutional power, it could also be seen as Ortiz's affirmation of a platform for continuing Native activism. Sherry Ortner, a peer of Ortiz in graduate school and a visitor at Princeton from 1969 to 1970, has proposed the manifestation of agency in two related forms: power and projects.[63] For subaltern peoples, she says, agency-via-power is often overt resistance, while agency-via-projects need not be.[63] Ortner gives the example of Tswana women who both directly resist cultural inculcation to passivity (agency-via-power) and embrace the Methodist cause (agency-via-projects).[63] Through respect for institutional rules, Ortiz gives himself opportunities for the expression of agency-via-projects, which for Ortiz is his scholarly activism in the larger movement for Native American sovereignty. This latter interpretation of the institutional identification with Princeton is better understood when considering the broader institutional-activist hybridity of the Convocation leveraged by activists such as Ortiz.

Writing the "Call for a Convocation," Ortiz writes that "the leadership and authority of the American Indian in all fields affecting our history, culture, economic improvement and social development must be asserted if any progress is to be attained for our people."[56] Clearly, the Convocation was a scholar-activist event. At the same time, the planning process took careful consideration of Princeton's interests, and of course, Ortiz takes his work and identity as a scholar as seriously as anything else. Ortiz, for instance, says in the aforementioned correspondence to Costo: "We simply don't want the University to get a black eye with its students and with reasonable men everywhere because of some outsider's personal jealousies and prejudices. We are scholars and educators here, not polemicists or politicians and we would like to keep it that way."[62] The "Call for a Convocation" emphasizes Native American sovereignty, but it also stresses the event's relevance for non-Native American "friends."[56]

The Convocation's institutional-activist hybridity produced an accommodation: a performance. The planners of the event took great pains to ensure how the Convocation would be perceived. In Ortiz's letter to the steering committee, he says, "We should like to go on record as believing that we like to hear from people who disagree with our views, because we learn from them."[58] Likewise, in Ortiz's letter to musician Louis Ballard, he says, "What we will not do ... is to gather ... so that ... the media can watch us kill one another off because of misunderstandings. Many non-Indians undoubtedly expect us to do this because it would reinforce their stereotypical view that we Indians cannot work together."[64] Again, while the Convocation's performativity and concern for outsiders' views may be considered a constraint on Native American agency, viewing the event as a beneficial accommodation underscores how it enacts agency-via-projects.

For example, in the "Call for a Convocation," Ortiz emphasizes how the event is an opportunity for the articulation of Native American leadership: "Especially lacking is the reasoned and disciplined voice of Indian scholars speaking in concert to the grand issues before our people and before the nation."[56] Rupert Costo, like Ortiz, sees the value of the event in training young Native American voices, asserting this in a letter: "We must dredge up and make articulate ... our best students, not alone for purposes of Convocation attendance, but to give them some sense of responsibility and bolster up their endurance in the current situation."[65] Critically, not only is the Native voice put to work, but non-Native American peoples are made to listen. As Ortiz states in the "Call for a Convocation": "Many people in this country, especially the young, look to the long-suffering but enduring Indian for inspiration and guidance ... People, not only in this country but elsewhere in the world, are listening for the voice of the American Indian."[56] Planning

documents show the wide range of non-Native American invitees, including those from organizations such as the National Education Association, the Donner Foundation, and the New York Times.[66] The presence of these entities is an act of political solidarity, echoing Deloria's point that "contacts at the higher levels of university administration, within the professional journals, or at competing universities" serve as protection for Native scholars' interests;[67] the hybridity of the Convocation manifests itself in part through these relationships with non-Natives. The setting of the Convocation, where so many non-Natives can be called into relation with Native American activists as listeners, is precisely where the potency of articulate Native voices can have a large impact. Accommodation through performance is an exercise of self-determination that counts, because there is a stake (listeners' impressions) involved.

In this way, Ortiz leveraged his institutional-activist hybridity to make possible an event—the Convocation—that was marked by its own institutional-activist hybridity. Like Native-educational hybridity, institutional-activist hybridity was not used for individual, but rather communal, gain. Returning to Deloria's statement that in his day, universities recruited Native American personnel "as high-profile Indians,"[54] in Ortiz's case, he certainly did not work for the sole purpose of enhancing his profile. Instead, Ortiz put his institutional affiliation to use so that a Convocation could be held at Princeton and address pressing political, legal, and social concerns of Native Americans.

The classroom context

In the classroom, Ortiz was simultaneously positioned as a Native activist and anthropology professor; I refer to this as his "anthropologist-activist hybridity." As evidenced by an assortment of course materials, this hybridity has two manifestations; indeed, the word "anthropologist" in the term refers to two distinct positions. The first is Ortiz's position between the anthropological *discipline* (and its knowledge) and Native American activism. The second is Ortiz's position between being an anthropology *professor* to mainly non-Native American students and Native American activism.

In regard to the first position, Deloria's *Custer Died for Your Sins* criticizes how anthropology determines others' truth and identity, uses cultural difference between whites and Native Americans to explain contemporary issues, and constructs theories and abstractions about Native peoples;[68] the book is emblematic of more widespread wariness of anthropologists by some Native Americans. Underlying Deloria's criticisms is a conflict between Native American knowledges and Western knowledge. How can anthropologists support Native American goals when anthropological knowledge is derived from Western ways of thinking? In addition to Native American individuals such as Deloria criticizing anthropology, Ortiz himself is, at times, critical of anthropologists, too. He laments anthropology's "25-hour-a-day practitioners and the utter irrelevance of so much anthropological research,"[69] and, in course notes for his 1973 course, "People and Cultures of Native North America," feels that "anthropologists ... have, knowingly or unknowingly, boxed us into categories which ... misrepresent, but often demean and debase the actual Indian cultures they purport to describe and analyze."[70] Despite the criticisms of anthropology by many Native activists and Ortiz's own admission of some anthropological problems, he believes in anthropology, particularly because he sees individual anthropologists as empowered to develop and utilize their own flavor of anthropology. In his presentation at the 1970 American Anthropological Association's (AAA) "Anthropology and the American Indian" conference, he argues that anthropology "can be abused, but it can also be used humanely and ethically, as well as scientifically. This depends on the individual and the personalities of anthropologists are as diverse as those of any other random academic category."[71] He refuses to lump all anthropologists together, believing that "those of us who do not come from the land of cultural background which fosters this [Western] attitude can reject categorically in our own work the neo-colonialist underpinnings and trappings."[72] Such logic aligns with Brayboy's feeling that Western-deriving knowledge can still be practiced in the classroom if it is applied for Indigenous ends.[7] Furthermore, with respect to the practice of anthropology today, the discipline continues to evolve as newer anthropologists work to refine their epistemological commitments.[73, 74]

The second hybrid position arises from Ortiz's unusual circumstances when examined through the lens of Paulo Freire's *Pedagogy of the Oppressed*. In his work, Freire distinguishes between oppressors and the oppressed, the latter of which have the sole capacity (and responsibility) to take charge in liberation.[75] In this context, Freire advocates a

dialogic, problem-posing teaching (where the teacher learns as much as his or her students) over a "banking" style of teaching; the former style results in liberation via education.[75] While a Freirean pedagogy might seem useful for a historically oppressed (through settler colonialism) population, it is not necessarily the case. Julie Kaomea, for instance, has studied elementary students' Hawaiian studies presentations on Hawaiian culture and takes issue with the student-centered approach, finding teachers to be complicit in students' colonial imaginaries of Hawaiians and their corresponding stereotypes.[76] Célèste Kee and Davin Carr-Chellman, in their investigation of Freirean approaches to Indigenous literacy in Canada, stress how a Freirean intervention "too easily operationalizes liberation as a universal concept that can be lived-out in the same way for all people in all places, ignoring the idiosyncrasies of liberation in diverse contexts."[77] In fact, the context of Ortiz's pedagogy is quite different from Freire's context, which centered the peasant class as the oppressed.[75] Ortiz's case has him as the oppressed (a Native American scholar) teaching the oppressors (primarily non-Native American students who are settlers on Native American lands). How can a Native scholar teach non-Native students in ways that further Native goals?

Through an analysis of archival materials, I will show how anthropologist-activist hybridity is productive for Native American goals in a predominantly white classroom context. By deploying anthropological knowledge in a subversive way and by practicing a pedagogy of provocation—which I identify as neither aligned with nor diametrically opposed to the stewardship of learning explained by Freire—Ortiz leverages anthropology for Native American activism.

The practice of anthropology

A comparison between Ortiz's approach to assigning authors for anthropological theory courses versus Native American Studies courses reveals major differences. In various reading lists for theory courses, primarily symbolic and structural, Ortiz draws upon traditionally canonical scholars including Lévi-Strauss, Turner, Geertz, Gluckman, Douglas, Rappaport, and Sahlins.[78–80] In notes for Native American courses he taught in 1973 ("People and Cultures of Native North America") and 1996 ("The North American Indian"), respectively, Ortiz sometimes omits anthropological texts, maintaining that he is "not anti-anthro but pro-Indian" and stressing the course aim of "learn[ing] about Indian cultures directly + Indian experiences directly ... [so the] readings focus on authentic Indian experience, rather than only on anthro interpretations of those experiences—distinction critical."[70, 81] This contrast suggests that Ortiz finds anthropological ways of thinking rather than obedience to canonical texts to be most important in his courses pertaining to Native Americans.

What are these anthropological ways of thinking utilized by Ortiz in teaching predominantly non-Native American students? A review of archival materials highlights Ortiz's belief in anthropology as a lens for viewing cultural diversity, in turn breaking down stereotypes, aligning neatly with Grande's hope that essentialist views of Indigenous peoples (leading to binary oppositions with non-Indigenous peoples) be eradicated.[8] For instance, in his 1968 syllabus for "Peoples and Cultures of the American Southwest," he outlines one course goal as understanding "the main axes of diversity among the Indian and Hispanic cultures of the southwestern United States and Mexico."[82] Or, in notes introducing his 1973 course "People and Cultures of Native North America" to students, he writes that "the term Indian is yours, and in proceeding from the arbitrary lumping denoted by that term there is a tendency to believe that there is a single Indian culture. This is not so ... I hope you develop a sense for the subtleties of Indian cultures, and a healthy respect for the tremendous divergences found therein."[70] Specific approaches, such as requiring each student to adopt, research, and present about a particular tribe,[83] or focusing on contrasts between distinct tribes, such as the Hopi and Navajo,[84] are a manifestation of this goal towards seeing Native multiplicity.

Many of Ortiz's courses derive from his research on major Native stereotypes that served particular purposes throughout American history. To Ortiz, anthropology offers the arena to understand power, that is, "how stereotyping shaped the nature of the encounter between white and red."[85] In doing so, students can "look at historical and contemporary Indian stereotypes and, hopefully, get beyond them."[85] Resonating with the earlier point about anthropology as an ever-evolving discipline, Ortiz also asks students to criticize older anthropological texts for their ethnocentrism. His

notes say, "As you read some of these grand generalizations and sweeping characterizations of whole peoples ask yourselves this question: Could these characterizations of whole people be true, or am I looking at a tidy and convenient system of Western categories overlaid on these cultures. Don't adopt a nihilistic attitude, please, but please do distrust familiarity of characterization when you find it."[86] One might wonder, of course, to what extent Ortiz's attention to diversity as a way of destabilizing a monolithic stereotype was a sensibility derived from his own hybridity. Ortiz's Native-educational and institutional-activist hybridity are important factors in his pedagogical decisions; by standing in front of non-Native students to teach, he is destabilizing a stereotype himself.

Ortiz's pedagogy is a form of cultural mediation, to draw on Terrence Turner's use of the term in a different context.[87] Through his teaching, Ortiz is converting his position as a researcher in the anthropological discipline into an instrument of Native American advocacy and sovereignty; in this way, he achieves anthropologist-activist hybridity. Furthermore, the cultural mediation concept underscores the way Ortiz's teaching reflects his responsibilities to the broader Native American community. Ortiz must be read as a community representative who professes anthropology, not a Western scholar solely interested in his own career.

A pedagogy of provocation

How does Ortiz espouse a pedagogy of provocation in relation to his students, and how is this productive for a Native American agenda? At the risk of obscuring the varied manifestations of this pedagogy, I use the term "provocation" to capture Ortiz's frankness and his intention to stir students to reflect. It is precisely the fact that this provocation is directed at non-Natives by a Native instructor that defines anthropologist-activist hybridity here.

One particular moment of provocation is in Ortiz's comments on two student papers from his 1972 Princeton course, "Native Peoples and Cultures of North America." The paper prompt is to compare John Neihardt's *Black Elk Speaks* and Peter Farb's *Man's Rise to Civilization*, and to consider weaknesses of each approach as well as raise further questions.[88] One student's paper finds deficiencies in Farb's work; reviewing Black Elk Speaks, the student says, "One of the only ways a non-Indian can learn about and come to understand Indian wisdom is through the Indian oral tradition ... Black Elk's words have meaning because he is Indian and because he has great personal wisdom ... Farb outlines the skeleton of Indian culture, Black Elk adds the flesh and blood and makes it live."[89] Ortiz approves of the paper but writes, "The distinction is also that between a true man of knowledge (Black Elk) and a pimp (Farb)."[89]

Another student's paper criticizes both Man's Rise to Civilization and Black Elk Speaks as "neither ... tries to understand the inner workings of persons from different cultures; neither ... searches further than his own culture for explanations."[90] Ortiz comments (as before) that he thinks Black Elk is "true knowledge" and Farb is "a pimp."[90] He tells the student, "You demonstrate here a piercing critical and analytical acumen; this assures you of successes in any competition and company around here, but you should also think about the hard questions of knowledge—knowledge for what? For whom? How can one avoid pimping for someone else in the pursuit of knowledge?"[90] These interactions, where Ortiz provides feedback to students, are a useful example of the provocation Ortiz produces in guiding students. As papers, both students' works can be read as intertextual translations in dialogue with Ortiz's course content and the works of Farb and Neihardt; additionally, the students certainly bring their own predispositions (towards anthropology and Native American studies) with them. Ortiz's comments, however—although they do not change the outcome of either paper—advocate a particular interpretation of Black Elk and Farb; in his comments to the second student, specifically, Ortiz distills epistemological questions for his pupil. Ortiz's students are afforded the space to develop their own responses, but this does not preclude Ortiz from being firm in his guidance of their thinking; hybridity is once again enacted through these generative Native to non-Native encounters.

There is also evidence that Ortiz seeks to optimize his limited opportunity to shape the thinking of his non-Native American pupils. In the aforementioned transcript from the UCLA panel discussion on a proposed American Indian Studies master's degree program, Ortiz emphasizes that a common Western view is to seek "objective truth" by dis-

tancing oneself from the past: "The further removed it is, the better it is."[41] In criticism of this perspective, he feels that the past can become dangerously obscure, to the point where "it's so far away, so receded, that it's too late ... We haven't got time to wait that long."[41] The (potentially subjective) interpretations that Native American scholars have to offer, in other words, are well worth sharing in the present, even if they don't fit the standards of Western objectivity. Ortiz also focuses on his limited time as professor in preparation for a temporary teaching role at Colorado College, explaining his capabilities and closing a letter by saying: "This is how you can best utilize me and my presence there for a block."[91] Perhaps a fully Freirean, dialogic approach to pedagogy is ideal, but Ortiz lacks time. A pedagogy of provocation makes good use of this time and enables Ortiz to carry out the larger project of Native American self-determination, which perpetuates Native American knowledges.

What becomes of provocation? Another interaction between a UNM student and Ortiz, captured in a 1990 letter, suggests an answer. Learning similar topics in Ortiz's course as the aforementioned students, this student says, "I certainly never thought of myself as a person who carrys [sic] around biases but obviously, after the discussion of the Farb book this morning, I have much to learn about me."[92] He goes on to write, "Hopefully, this will help me to become more aware of what I need to know about the past and inevitably, the present."[92] This scene suggests the fruitful outcome of class discussions under Ortiz's purview: transformative learning that Jack Mezirow advocates, where "learners become aware and critical of their own and others' assumptions."[93] Moreover, the student suggests that the morning class session may have triggered emotions of surprise and guilt, aligning with Megan Boler and Michalinos Zembylas' pedagogy of discomfort, where "by closely examining emotional reactions and responses ... one begins to identify unconscious privileges as well as invisible ways in which one complies with dominant ideology."[94]

Still, Ortiz's provocations are compatible with students' own synthesis of course content; Ortiz may not embrace a truly Freirean pedagogy, but he isn't anti-dialogic, either. While some examinations focus on content recall,[95, 96] epitomizing the anti-Freirean "banking scheme," others ask students to think for themselves. A 1975 final exam question for Ortiz's "Indian/White Relations" course reads, "Why, by your reading of Brown's book, supplemented by class discussions, was the stereotype not based on a tribe from the Southwest or Northwest or from some other region?"[97] Or, in a 1980 final exam question for "The North American Indian" at UNM, Ortiz writes: "It has been argued in class that N. Scott Momaday presents an authentic Kiowa tribal experience in his book, *The Way to Rainy Mountain*. It has also been argued that the book represents a good 'bridge' between Indian traditional knowledge and history. If you agree that both assertions are true, what evidence can you bring to bear to prove that each is, indeed, true? ... If you would like to argue against both assertions above, please feel free to do so."[98] A pedagogy of provocation is not meant to be wholly didactic; instead, it serves as a guide and an impetus for reflection, and through it, students are called into relation not only with Ortiz (as their professor) but with broader Native American thought. It is not only that Ortiz practices hybridity in his anthropologist-activist encounter with non-Native pupils, but that pupils also begin to develop a hybrid position in newfound association with Native communities, of which Ortiz is a representative.

In summary, Ortiz leverages anthropologist-activist hybridity to—with the discipline of anthropology—subvert hegemonic notions of Native Americans and—when teaching with a pedagogy of provocation—guide and challenge individual students' knowledge, at times stirring uncomfortable but beneficial self-reflections. Ortiz has the agency to practice a pedagogy of his choice, so while anthropology is a Western discipline, Native American goals remain front and center. A commitment to these communal goals—as is shown when reading Ortiz's pedagogy as a form of cultural mediation instantiating relations with the Native American community—goes far beyond any individual rationalities.

CONCLUSIONS

This paper has focused on hybridity—a positionality emerging from Indigenous peoples' contact with non-Indigenous institutions, epistemologies, and people—in higher education. Moving across the Native community, institutional, and classroom contexts of Alfonso Ortiz's career has revealed the productive—rather than detrimental—potential of hybridity for indigenizing education. A key theme across each of the contexts examined might be called "leveraging." In the

Native community context, Ortiz encourages Western university credentials to be leveraged; in the institutional context, a Western university's power, resources, and stage are leveraged; and in the classroom context, Western ways of thinking that subvert stereotypes and an opportunity to confront non-Native American students are leveraged.

What I do not wish to show is a dependency: it is not that Indigenous priorities *rely on* an interaction with non-Indigenous institutions, epistemologies, and people to be productive. On the contrary, I have been interested in how Indigenous priorities might remain prioritized when a Native student attends a predominantly non-Native college, a Native activist finds a job at a Western institution, and a Native scholar finds himself in front of non-Native students as a practitioner of a discipline with Western origins. Additionally, while hybridity enables individual actors' agency, in Ortiz's case, the coupling of this agency with communal rationalities (rather than individual ones) makes hybridity productive for Indigenous goals.

An analysis of hybridity is important as Indigenous scholars continue to think about relationality; Ortiz's hybridity raises questions for "making kin"[10, 99] or "situat[ing] groups in relation"[13] in higher education settings. If Native-educational hybridity produces tools for Native community empowerment, how might universities come to terms with the fact that, in the service of Native students, the knowledge they provide is but complementary to the wealth of Native knowledge the students receive at home? If institutional-activist hybridity produces a platform for Native American activism, how can NAS programs, especially those based in predominantly white institutions, better design themselves as conduits for Native American activism? And if anthropologist-activist hybridity produces a subversive lens for non-Indigenous students, how might other disciplines support the questioning of hegemonic discourses about Indigenous peoples?

This paper has based the hybridity concept on multiple positionalities and applied the hybridity concept to understand relationality. Why not, then, simply think in terms of positionality and relationality, rather than introducing the hybridity concept? In the first instance, using "hybridity" points to Ortiz's capacity to leverage a particular set of positionalities. Ortiz certainly has other positionalities (father, husband, male), but this paper has argued how specific positionalities become generative opportunities for Ortiz and the larger Native American community. To think only about positionality, not hybridity, would miss the point that certain positionalities are uniquely productive. As for the question of relationality, much of the insight about relationality was made possible by first following Ortiz's hybridity. Hence, hybridity is a launching pad for uncovering particular relationalities that might not have been identified if the focus was on relationality, broadly defined, from the start.

Beyond continuing to explore Ortiz's career as an inspiration for the current indigenizing movement—for there are more archival materials to be analyzed—more work must be done to rethink the West's responsibilities if it is brought into relation with Indigenous faculty, students, and communities. As powerful as hybridity can be for Ortiz, the onus remains on him to leverage it. What if Western institutions, disciplines, and non-Indigenous students actively supported, rather than simply created the positional circumstances for, Indigenous peoples' hybridity? Scholarship has demonstrated that Native American students' sense of belonging at universities is a persistent issue.[100] How much more beneficial might, for instance, an experience at a Western university be for a Native student if the institution amended its purpose to explicitly support such students' transformational resistance? There is also room to think about whether hybridity is something that can inform the practice of non-Native educators and students. The corpus analyzed for this paper belonged to a Native scholar, and the discussion above pertains to the hybridity practiced by Ortiz, but might hybridity be a structuring concept for incorporating Native content into mainstream classes? How might the concept be a model for how non-Native students engage in learning alongside Native students?

If settler colonialism is a structure,[1] it is certainly a structure that is forever incomplete. As this paper has shown, one of the structure's key openings is in the opportunities for Indigenous hybridity. When Indigenous students and teachers

take advantage of these opportunities, they can assert and build their sovereignty while calling non-Indigenous people and institutions into new relations, two goals essential to the process of indigenizing higher education.

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PRESS SUMMARY

Many Indigenous scholars have called for indigenizing higher education as part of the larger movement towards decolonization. As it exists currently, the American higher education system sets up Indigenous students and faculty members to engage with non-Indigenous institutions, people, and ways of thinking. This study explores how one particular Native American faculty member, Alfonso Ortiz, commits to Indigenous goals while also relating to non-Indigenous entities, including Western universities, Western-derivative disciplinary knowledge, and non-Native students. I explain how he leverages engagement with non-Indigeneity to advance Native American communities and activism.

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