Research Article

The Ecology of a Bite: Environment, Evolution and Diet in Gray Foxes

Joseph Zhang

Walnut High School, 400 Pierre Rd, Walnut, CA 91789, USA

ABSTRACT

Inhabiting the channel islands, island foxes have a basic habitat compared to mainland foxes. Environmental data (human impact, prey availability, habitat) from Google Scholar and morphometric data (trigonid & talonid length and area) from the University of California, Los Angeles's Dickey Collection were integrated to gain a comprehensive understanding on whether and the extent determinants contribute to shaping tooth morphology and diets in gray foxes. Methodologically, logistic regression predicts binary dietary preferences, multiple linear regression exhibits the degree of the environmental variable's influence on BTG ratio, cluster analysis groups sets of environment controls together to uncover distinguishing traits or behaviors, and hypothesis testing determines the statistical significant differences in the mean BTG ratio between foxes to examine whether habitat type has a pronounced effect on the tooth structure. Subsequently, the multiple linear regression revealed habitat and human impact to be significant, but prey availability to have a marginal role. Although predicting meat diets was high, the logistic model's performance was poor for plant diets, and an issue of imbalance in the dataset seemed a likely cause. Representing meat and plant diet, cluster analysis corroborated the habitat and diets' role in dictating the tooth anatomy. Ultimately, the one-way ANOVA didn't identify significant variation among mainland and island foxes for BTG ratios ($F = 2.18$, $p = 0.15$), suggesting that habitat type isn't a significant influencer. Concluding these findings about the evolutionary ecological mechanisms and environmental morpho-ecological traits, future studies could build on these observations through seasonal variations and genetic analysis.

Keywords: gray foxes; habitat; morphology; diet; regression; prey availability

INTRODUCTION

Gray foxes live in diverse regions around the world such as in the channel islands. They possess the unique ability to thrive in many environments, and as such, their diet varies widely across different regions (7). Mainland foxes, with their greater ecological diversity, can consume a wider range of food types including more meat, while island foxes, having less ecological diversity, may have a more limited diet that includes more fruit or insects (7). To adapt to these diets, gray foxes have specialized carnassial teeth with a special blade-for cutting meat, and the grind for chewing up other foods, such as nuts, berries, and shrubs (7). Previous studies from *The Nature Conservancy* and *Mammalian Species* indicate mainland gray foxes have a more diverse diet than their sister

Corresponding author: Joseph Zhang, E-mail: zhangjoseph21@gmail.com.

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species, the island fox, with increased consumption of meat (14). Given this, it is postulated that there could exist a correlation between the diet and the ratio of blade to grind portion due to the differing diverse diet and land size for mainland and island foxes (11).

A gray fox biome is a terrestrial region that is categorized by the intensity of temperature and precipitation level (9). First, there are ecologically diverse forests that many organisms call home (9). Second, there are grasslands that are dominated by dense vegetation and herbivores. That said, mainland foxes face slightly higher human impacts than island foxes due to the fact that they are located in urban areas. Constantly being developed in urban cities, human infrastructure triggers disruptions to the natural life of mainland foxes such as noise pollution, light pollution and habitat fragmentation. Conversely, channel islands reside in a more pristine environment with less human disturbance (9). Instead, these foxes tend to face setbacks that come from invasive species. Furthermore, islands are smaller than mainland which means they support fewer species (9). Nonetheless, the channel islands contain distinct species with unique evolutionary adaptations to thrive (10). And if there will be a decrease in large apex predators, it will mean for island foxes to have a more opportunistic diet like the mainland foxes. Island foxes will have less pressure and more time to forage for food. In spite of everything, islands are still limited in resources which leads to more competition and a continuous vicious cycle.

Since environmental influences vary in different locations (theory of island biogeography), so will morphological traits and feeding behaviors as well (7). Rightfully so, islands contain less resources and meal options (11). Accordingly, this leads me to delve deeper to analyze the difference in the carnassial tooth forms between mainland and island gray foxes. In light of this, I hypothesize that mainland gray foxes will have a larger trigonid to talonid area ratio in their carnassial teeth in contrast to island foxes. Due to increased ecological and prey diversity, it will enable morphological adaptations for mainland foxes to have a more carnivorous diet (13). Mainland foxes are already bigger than island foxes in terms of body size, so there is conclusive reason to believe that mainland foxes will increase their carnivorous diet (6). On the other hand, the grind area of island gray foxes is comparatively larger than the blade area of their carnassial teeth because they need to chew on softer food such as fruits and insects (11). Due to a more restricted diet, it will enable morphological adaptations for island foxes to have a more herbivorous diet. On top of that, mainland foxes will be negatively affected by urban areas compared to the island foxes. For example, foxes inhabiting the mainland regions would have to deal with obstacles such as finding food in the harsh cities and constantly putting themself in the risk of cars. Once again, island foxes can maintain a more natural behavior and living style as they are unaffected by urbanization (7). Overall, diet can really change because the whole process of obtaining food in cities and islands is vastly different, leading to alterations in tooth morphology overtime.

The goal of my research is to find out how biome elements like habitat, prey availability, and human impact shape the dental morphology and dietary choices of gray foxes. Ecologically, I will compare populations on the mainland to the populations on the Channel Islands to understand how these environmental predictors differently influence tooth structure and dietary habits. I want specifically to investigate, over a long period, how tooth shape in the foxes changed through photographs taken at a range of angles of both island and mainland gray fox's teeth. I will then use ImageJ to calculate and record the grind and blade length, and area, and then work out their ratio. I will then use three approaches to investigate how environment, prey availability, and humans affect gray foxes' morphologic characters like tooth shape and diets. I will use multiple linear regression in an attempt to understand in a lot of detail how environment, prey availability, and humans affect their morphological characters (3). That said, I can calculate them individually and then see them in terms of how they contribute towards adaptations in environments of the foxes. With cluster analysis, I will classify foxes in terms of similar physiological and nutritional characters (13). As a result, I am able to see the environmental impact on physiological, nutritional characters and consumption behavior in the foxes. Then, I will use logistic regression to investigate the odds of a gray fox with a specific consumption behavior in relation to its environment. Logistic regression is specifically useful in predicting categorical characters, such as preference for fruit or meat, and its impact (11). Lastly, this multifaceted approach will provide representative evidence to assess my hypothesis. This research will provide fresh insights on the traits and behaviors of gray foxes in totally different settings. The comparison of mainland and island foxes will show how adaptations like tooth shape are influenced by habitat, prey availability, and human influence. This will help us understand how foxes adjust to different environments. Moreover, this study's conclusions can have profound ramifications for conservation. For instance, in places where gray foxes are threatened by urbanization and habitat loss, really understanding how they have adapted can help us develop more effective protection strategies for them (13). Even more, this research can provide insights on how gray foxes respond to climate change and raise awareness about it.

METHODS AND MATERIALS

The analytical data set aimed at comparing and analyzing trends sums up to 36 gray foxes from mainland and island. The quantitative and comparative data from the UCLA Dickey Collection is collected rawly by which it was utilized to spot patterns and draw conclusions from (12) (Table 1). With that, a manageable sample size of gray foxes were chosen due to the island foxes being threatened due to diseases (14). This course of action was made in order to prioritize gathering high-quality data while enabling concentration on a small number of individuals from these vulnerable categories. Without overusing these vulnerable creatures, the data can be carefully evaluated. In addition to honoring conservation efforts (6), this targeted strategy enables a more thorough analysis of the

Table 1. The List of Variables and Associated Definition and Descriptive Statistics

Variables	Type	Definition	Descriptive Statistics	
Habitat	Categorical	Geographical location of either mainland or island fox	Mainland - 24	Island - 12
Prey Availability	Categorical	Classification of prey availability abundance (low, medium, high)	Low - 0 Medium - 22 High - 10	
Human Impact	Categorical	Whether habitat is influenced anthropogenically or not	Mainland - 24	Island - 12
Dietary Preference	Categorical	Type of diet (meat or plant)	Mainland Meat - 13 Mainland Plant - 8	Island Meat - 10 Island Plant - 2
Talonid Area	Numerical	A measurement of the grinding portion of the tooth associated with chewing plants	<u>Mainland</u> Mean - 22.63 Median - 21.465 SD - 4.14 Range - 12.833 Max - 29.541 Min - 16.708 Skewness - +	<u>Island</u> Mean - 18.14 Median - 20.1956 SD - 2.44 Range - 6.94 Max - 23.314 Min - 16.375 Skewness - Slightly +
Trigonid Area	Numerical	A measurement of the cutting portion of the tooth associated with slicing/ tearing meat	<u>Mainland</u> Mean - 20.32 Median - 20.4513 SD - 2.4 Range - 7.928 Max - 24.56 Min - 16.63 Skewness - 0	<u>Island</u> Mean - 16 Median - 17.102 SD - 1.38 Range - 5.2 Max - 19.53 Min - 14.33 Skewness - Sightly +
Blade-Grind Ratio	Numerical	A ratio of how much cutting to how much grinding which reflects dietary adaptation	<u>Mainland</u> Mean - 0.5198 Median - 0.5124 SD - 0.0497 Range - 0.1813 Max - 0.5980362148 Min - 0.4167311002 Skewness - 0	<u>Island</u> Mean - 0.5867 Median - 0.5576 SD - 0.0411 Range - 0.1303 Max - 0.5936900589 Min - 0.4634338403 Skewness - 0

distinctive traits of these foxes. Furthermore, the problem of unnecessary variation can be eliminated which makes it a lot easier to spot clear trends and differences between mainland and island foxes (13). This dataset includes all sorts of different aspects of tooth morphology data such as length, point of view, and ratios. With this statistically manageable dataset, the idiosyncratic data can be used to closely study the objective (7). Since it's from the well-known UCLA Dickey Collection, this study's data is gathered from well-preserved specimens which ensures accuracy and reliability. In addition, the collection has been around for nearly 100 years which allows trends to be studied over time (15). On the side, the guidance of UCLA professor Johnataon Marcot was truly crucial during the data collection process: provided the appropriate equipment/techniques to accurately photograph foxes, made sure that camera was calibrated and fox position was correct. With all this, the specificity of the data collection is well controlled.

The research was conducted through a mix of methods including Multiple Linear Regression, Cluster Analysis, Logistic Regression, hypothesis testing, and dietary preference modeling. Of course, each method will be described with concise detail.

Multiple Linear Regression

The aim is to understand how explanatory factors — habitat, prey available, human impact — lead to the foxe's unique morphological traits which are response variables (Tranmer, Murphy, Elliot, & Pampaka, 2020). Then, this cause and effect relationship will explore how the environment shapes gray fox's dietary habitats. Furthermore, it can be closely seen on how each determinant affects the carnassial teeth. Specifically, the multiple linear regression model will dive deeper into how these factors (IV) influence the blade to grind area ratio of the carnassial teeth (DV). By the end, the influence and importance of each factor will reveal itself through this test. The model can be written as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \cdots + \beta_k X_k + \varepsilon$$

- Y is the BTG ratio of the carnassial teeth (dependent variable)
- Xi's are the group of explanatory factors: habitat type, prey availability, human impact (independent variable)
- Bi's are the corresponding coefficients that estimate influence of the factors

Cluster Analysis

K-means cluster analysis (4) was performed by grouping the foxes by their environmental and morphological attributes to explore not immediately present structures in the data. Accordingly, a sample size of 36 gray foxes from three mainland populations and four island populations was included in the dataset. Three sets of predictors are as follows: Morphological (talonid/trigonid area and BTG ratio), Dietary (meat/plant), and Environmental (mainland/island). With that, k-means clustering presents itself as the most optimal multidimensional option to group the foxes efficiently for interpretation. Z-scores were utilized to standardize the continuous variables. As it is largely used in ecological analysis, Euclidean distance was used as the proximity measure between the features to represent meaningful biological clusters – whether they are near or distant. In addition, via the elbow method, the ideal number of clusters (k) was set. Overall, this method of analysis will validate if gray foxes with similar tooth morphology and environmental settings will also have the same diet. Simultaneously considering all predictor variables, the independent variables were jointly observed for and clusters were assumed to be roughly spherical in shape. The model can be written as follows:

$$arg\ min \sum_{i=1}^{k} \sum_{x \epsilon C_i} \| x - \mu_i \|^2$$

- C is representative of all clusters
- k is number of clusters
- $x \epsilon C_i$ means a fox was assigned to i cluster
- μ_i is the average fox in the group based on traits
- $\| x - \mu_i \|^2$ is the euclidean distance squared between a fox and their cluster which depicts how close or far away they are from the other foxes in the same cluster

Logistic Regression

Logistic Regression generates the likelihood of a dependent response variable in relation to multiple independent variables. Accordingly, a sample size of 36 gray foxes from three mainland populations and four island populations was included in the dataset. The goal is to determine if the gray foxes have a meat or plant based diet. The dependent variable – Dietary preference – originally was categorized into four categories: mainland meat, island meat, mainland plant, and island plant. However, these four categories were eventually simplified into two categories by binary digits: meat (0) and plant (1). The independent variables contain the talonid/trigonid area (sharp/chew (mm^2), BTG ratio, habitat, prey availability, and human impact. Z-scores were utilized to standardize the continuous variables. Most importantly, this method will predict the likelihood of a fox's diet based on multiple predictor variables. The fox observations will be independent and there exists no perfect multicollinearity. The model can be written as follows:

$$P(y = 1 \mid X) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n)}}$$

- $P\ (y = 1 \mid X)$ represents the odds of the gray fox having a plant based diet (mainland or island)
  0 = meat based diet
  1 = plant based diet
- β_0 is intercept (baseline log-odds when predictors = 0)
- $\beta_1 \beta_2 \beta_n$ are the coefficients that represent the degree of influence of each regressor
- $X_2 X_n$ are the predictor variables (Trigonid/Talonid Area, Habitat, Prey Availability, BTG Ratio, Human Impact)

Hypothesis Testing

With one-way anova, the tooth morphology, specifically blade to grind area ratio of mainland and island foxes which is the continuous response variable can be accurately tested to determine the significant difference by the categorical explanatory variable of habitat type (Mainland vs Island). With that difference, it showcases the gravity of the impact of the environment on tooth morphology.

Null Hypothesis H_0: There will be no significant difference between mainland and island gray foxes's BTG ratio. The model can be written as follows:

$$\mu_{mainland} = \mu_{island}$$

Alternative Hypothesis H_A: There will be a significant difference between mainland and island gray foxe's BTG ratio. The model can be written as follows:

$$\mu_{mainland} \neq \mu_{island}$$

One-Way Anova: The model can be written as follows:

$$F = \frac{Between - Group\ Variance}{Within - Group\ Variance} = \frac{MS_{between}}{MS_{within}}$$

- $MS_{between}$ is the mean square value between the groups and its variation is attributed to habitat differences
- MS_{within} is the mean square value within the groups and its variation is attributed to habitat differences on a individual scale

RESULTS

Multiple Linear Regression Results Blade ⇔ Grind Area Ratio

The three key covariates were habitat type (Mainland/Island), prey availability (low/medium/high), and human impact (yas/no). Throughout this test, it was crucial to analyze if any changes in the fox's environment corresponded to any significant differences in the fox's carnassial teeth, specifically the blade to grind ratio. Due to different proportions of the BTG ratio between different regional foxes as displayed in Figure 1, we could shed light on their extraordinary adaptive reflexes in response to environmental and human factors. The BTG ratio represents the proportion of blade (trigonid) and chew (talonoid) on the carnassial teeth. Rightfully so, a greater BTG ratio signifies the fact of a diet better equipped at shearing meat than grinding plants. The different proportions engenders ecological shifts through either a more omnivore or herbivore diet.

As shown in Table 2, the R-squared value was 0.238 which means that the three regressors explained 23.8% of the variance in the blade-grind ratio. Generally, a 30-50% R-squared value generates very meaningful results for ecological studies. Nevertheless, there are still more explanatory variables that hugely account for the variances of carnassial teeth. Second, the f-static value determines if the input and output variables have a statistically significant relationship. Looking at Table 2, the p-value for f-static is 0.0257 which is less than 0.05 which means that at least one of the predictors had contributed impactfully to the diet outcome. Specifically, the p-value for habitat type and human impact are both 0.008 while it was 0.201 for prey availability. Essentially, the habitat and

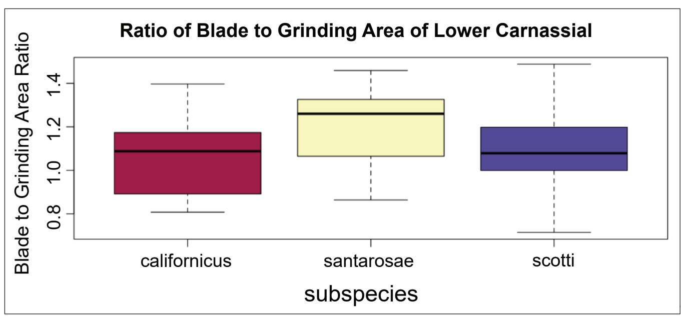

Figure 1. Blade to Grind Area Ratio (Lower Carnassial) of Different Regional Mainland Gray Fox Subspecies.

human impact had a significant impact on the blade-grind area ratio while prey availability had little significance. For the habitat coefficient, it means that whenever habitat alters by one unit, it will equate to how much the ratio changes as well. Table 3 shows that we have a -0.0253 coefficient. Pretty much when a fox migrates to an island, the BTG ratio will decrease by 0.0253 mm. This hints at an adaptation towards a diet less reliant on meat due to a greater area of grinding surface. Likewise, when a gray fox migrates to a mainland with human impact, the BTG ratio similarly will decrease by 0.0253 mm. This implies that the gray foxes there had access to non-meat food sources. Furthermore, when prey availability is medium compared to low and high, the BTG ratio will decrease by 0.0257. This effect does not really display a strong effect on BTG ratio when compared to human impact and habitat.

All in all, when foxes reside on islands or human impacted regions, the environmental pressures force the foxes to shift to a more omnivorous diet than a carnivorous diet. As illustrated in Figure 2, we can see that the reduction of the island fox's trigonid area is a flexible response to less prey diversity and ecological niches in relation to human presence. Overally, the significant predictors (habitat and human impact) and non-significant predictor (PA) explains roughly 24% of the variance in BTG ratio, but other factors may be just as important. From the ecological and human disturbances, we are provided with strong evidence that the fox's tooth morphology is constantly evolving under new circumstances. Moving on, this topic can be further explored with the rapid global environmental changes.

Linear Regression Results Gray Fox Dietary Preferences

The logistic regression provides a wonderful insight into gray fox dietary preferences, which is denoted by 0 for meat diet and 1 for plant diet. With an accuracy score of 0.80 as indicated in Table 4, this model initially explains itself with solid predictive power regarding correctly classifying the dietary preferences of gray foxes in majority of the cases. Nevertheless detailed in Table 5, a thorough glance at the confusion matrix and performance metrics reveal its limitations via class imbalance. On the bright side, the model had a perfect recall for instances of class 0, depicting the meat diet, which was identified correctly 100% without error. Indeed, the model is very sensitive when it makes distinctions for meat-based diets. Inversely, class 1 recall is significantly lower, at 0.50, meaning half of the true plant diet cases were misclassified

Table 2. Model Summary Stats

Metric		Value
R-Squared		0.238
Adjusted R-Squared		0.181
F-statistic		4.206
p-value		0.0257
Degrees of Freedom	*Model* / *Residual*	2 / 27
AIC		-105.4
BIC		-101.2

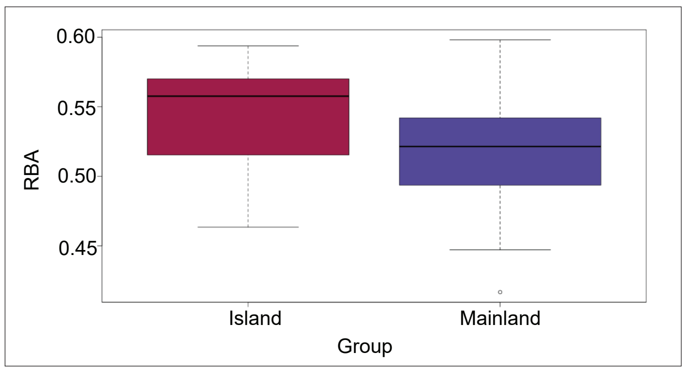

Figure 2. Relative Blade Area between Island and Mainland Gray Foxes.

Table 3. MLR Results for Key Covariates

Variable	Coefficient	Standard Error	t-value	p-value	95% CI
Intercept (Constant)	0.5681	0.022	25.814	0.000	[0.523, 0.613]
Habitat Type (Island)	-0.0253	0.009	-2.887	0.008	[-0.043, -0.007]
Human Impact (Yes)	-0.0253	0.009	-2.887	0.008	[-0.043, -0.007]
Prey Availability (Medium)	-0.0246	0.019	-1.311	0.201	[-0.063, 0.014]

by the model to be meat-based.

From this, a clear indication arises that the model fails to identify true instances of plan diets. The major problem points to a big imbalance in the data whereby the occurrences of meat-diets outnumber the plant diets. Hence, this model has a bias towards meat-based diets. Plus, it does not accurately portray a fair generalization even with evidence of a major shift towards plant diets.

From an ecological perspective, the credibility of this model can be overlooked as it does not contribute to the breaking understanding of gray fox evolution and its flexibility against harsh environments (human impact and low prey).

Though the model's performance potentially may be promising, there are quite a few places where it can be further improved. First, we can oversample the minority group (plant diets) artificially. Vice versa, we can undersample the majority group (meat diets). To further neutralize the imbalance, we can gather more additional data on plant diets.

Hypothesis Testing Results Anova

According to Table 6, the one-way anova result had a rounded f-static value of 2.18. To note, a f-static value near 1 represents no significant difference while a f-static value close to ⅘ represents a substantial significant difference. So, the moderate 2.18 f-static value isn't necessarily a strong indicator of a wide significant difference between the BTG ratio of mainland and island foxes. Indeed, the p-value is the primary determinant of significant difference between two groups. Referring to Table 6, the p-value was 0.15 which is less than the significant level of 0.05. Therefore, my null-hypothesis cannot be rejected.

With that, there is no statistically significant difference of the BTG ratio between mainland and island foxes. Overall, it has been concluded that the habitat type is not a major factor affecting BTG ratio. Nevertheless, a larger sample, more regressors, and even a manova test can give a more comprehensive and conspicuous view of this situation.

Cluster Analysis Results

Based on physical traits, prey availability, dietary preferences, and habitat, the foxes were grouped by these factors through k-means clustering. The aim was to dive deeper into underlying patterns of ecological/biological factors influencing the clusters. It was categorized into three clusters.

Using the Principal Component Analysis (PCA), the data has been visualied into a scatter plot with different colored dots to symbolize different clusters as illustrated in Figure 3. As evidenced in Table 7, each cluster's mean

Table 4. LR Results for Meat or Plant Diet

Metric	Group 0 (Meat Diet)	Group 1 (Plant Diet)	Macro Avg	Weighted Avg
Precision	0.75	1.00	0.88	0.85
Recall (sensitivity)	1.00	0.50	0.75	0.80
F1-Score	0.86	0.67	0.76	0.78
Support	3	2	5	5

Table 5. Confusion Matrix

	Predicted Meat (0)	Predicted Plant (1)
Real Meat (0)	3	0
Real Plant (1)	1	1

Table 6. Anova One-Way Summary Table

Metric	Value
F-statistic	2.18
P-value	0.15

Table 7. Carnassial Teeth Metrics by Cluster

	Blade Area	Grind Area	BTG Ratio	Blade Length	Grind Length
Cluster 1 (cyan)	20.2	18.1	0.52	36.62	5.83
Cluster 2 (yellow)	25.6	22.9	0.50	45.7	6.43
Cluster 3 (purple)	5.6	4.5	0.49	44.96	5.63

feature values denote mean feature values for the group of foxes in that group. In Cluster 1, a relatively intermediate blade and grind areas can be noticed in a pattern, possibly indicative of diets in these foxes in habitats with both plant and small animals' diets dominating them. Smaller blade and grind areas can be noticed in Cluster 2, possibly indicative of diets in these foxes possibly with a focused (specialized towards flesh-eating and possibly environmentally supported in such a manner) direction. In Cluster 3, with largest blade and grind lengths, diets in these foxes can be noticed to have become general, possibly omnivorous, and possibly larger and bulkier in overall shape, and these can be noticed in relation to mainland habitat and increased availability of foods.

Cyan: Represented in Cluster 1, these foxes have relatively intermediate blade and grind areas, with an intermediate proportion of blade-grind areas. Island habitats and a mixed diet of both plant and small matter can be noticed in these animals.

Yellow: Represented in Cluster 2, these foxes have a smaller blade and grind areas and a larger proportion of grind-to-blade. In its diet, meat is most prevalent, possibly in island habitats with a focused availability of foods.

Purple: Represented in Cluster 3, these foxes have largest blade and grind areas, and a general omnivorous diet can be noticed in them. In these, prey availability in mainland habitats can be noticed, with a larger variety, and a larger range in terms of intake can occur in them. The color-coding in a scatter plot enables one to visualize such clusters with ease. That three groups in a PCA plot have a differentiation proves not only numerical but even visualization differentiation in clusters. That visualization is an important part in testing compliance with the hypothesis that one can classify gray foxes in terms of environment, morphology, and diets.

From the output, K-means clustering grouped the gray foxes into three groups with distinguishing characters, with a specific feature for each group. Analysis conforms with our first hypothesis that environment (diets and habitat) and food preference contribute a lot in defining the morphological characters of gray foxes. The yellow (Cluster 1) corresponds with an intermediate general diet (plant and possibly small prey) and intermediate morphological characters. Perhaps, in island habitats, such an environment could have a less specific diet and intermediate physical characteristics supportive of consumption of both plant and prey matter. In the same vein, Figure 4 depicts a reduced occlusal area in island relative to mainland foxes which further hints at a shift from carnivorous dietary habits. The yellow (Cluster 2) corresponds with a meat-eating diet and smaller, specific morphological characters supportive of such a diet. As per the data, such animals could have high adaptability in terms of environments with little availability of plant matter but with high availability of prey matter, such as islands with less availability of plant matter. The purple (Cluster 3) corresponds with larger dimensions and a general omnivorous diet. Such animals could have derived from habitats in the mainland, with high availability of prey in terms of variety and abundance. The larger blade and grating areas confirm that such animals have a high demand for strong morphological characters for consumption of a high variety of foods.

The K-means clustering analysis has delivered significant insights into habitat, dietary preference, and gray fox morphology relationships. Island and

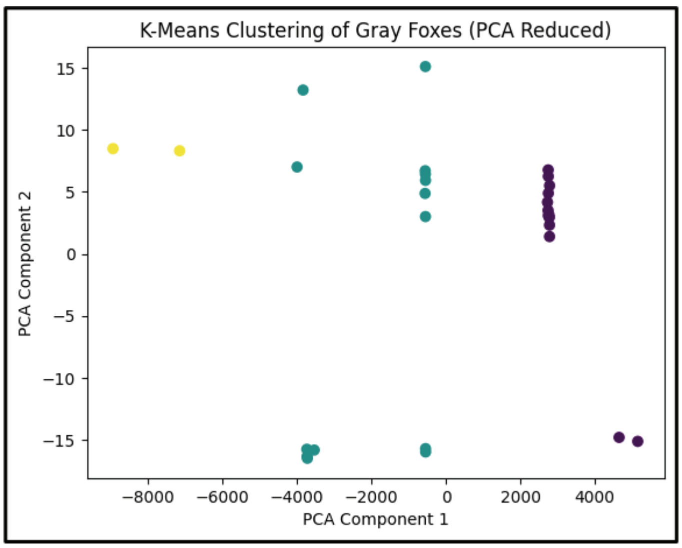

Figure 3. K-Means Clustering After PCA Dimensionality Reduction.

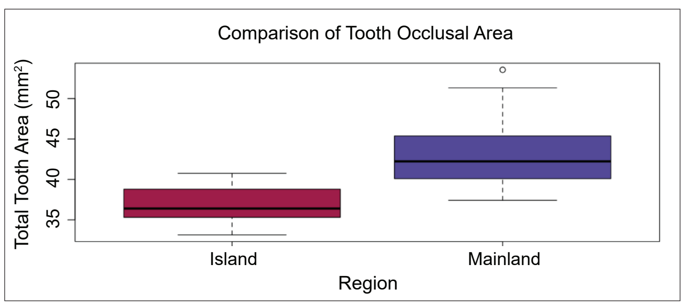

Figure 4. Total Occlusal Tooth Area (mm^2) between Island and Mainland Gray Foxes.

mainland populations have a discernible clustering, and a differentiation between them in terms of habitat and diet, suggesting an adaptation of gray foxes' physical traits to habitat and diet. The application of K-means clustering, facilitated through visualization with PCA, has facilitated the establishment of meaningful groups that confirm the hypothesis of environmental and dietary impact on morphology. Increased use of sophisticated clustering algorithms and incorporation of additional environment factors could extend and deepen such an analysis, providing a deeper level of understanding of ecological and evolutionary factors driving the variation in gray foxes. The findings indicate that habitat and dietary preference contribute significantly to an important role in driving variation in gray fox morphology, and future work could involve an expansion of datasets with additional factors such as location, seasonality, and reproduction. Verification of clusters through additional, external datasets such as genetic analysis and behavior studies could add additional robustness to such a conclusion.

CONCLUSIONS & RECOMMENDATION

The aim of this study was to assess the impact that environmental factors, (habitat type, prey availability, and human impact) usually linked to morphological traits and food preferences in gray foxes, have on the carnassial teeth structure – specifically encapsulated by the blade-to-grind area ratio. The results obtained using multiple linear regression, logistic regression, and cluster analysis show that habitat type and human impact have been critical in molding morphology and diet in gray foxes, more so on islands. It showed that habitat type (mainland versus island) and human impact were the best predictors of tooth morphology, while island foxes had smaller blade-to-grind ratios, indicative of dietary adaptations to limited resources. Whereas prey availability did have some influence, it was relatively less influential compared to the morphological variation that was observed. This reinforces the hypothesis that environmental factors, especially habitat and human disturbance, are major contributors to adaptive traits in gray foxes. Cluster analysis, which revealed distinct divisions based on physical traits, diet, and environment, provided more evidence for these. The three groups, which represent omnivore versus meat-based diets and island and mainland settings, demonstrate the obvious connection between morphology, diet, and habitat. Such results would indicate that gray foxes have developed adaptive traits linked to specific ecological pressures, like prey availability or habitat type, and further strengthen the link between environmental factors and physical traits. The logistic regression model was highly correct in dietary preference, mainly meat-based diets, though the plant-based diet had a bit of a challenge, which emanates from an imbalance in the dataset. However, despite those challenges, this model offers some important lessons about how gray fox diets are influenced by their environment.

In all, the study gives insight into how ecological and environmental factors drive the evolutionary adaptations of gray foxes, with important implications for their conservation and species management. Further, this work can be extended by future studies to include other environmental variables, seasonal influences, and genetic analysis that may give further insights into the adaptations of gray foxes. Moreover, further understanding of the genetic basis of these morphological traits may strengthen the associations between environment, diet, and evolution in gray fox populations.

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