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RESEARCH ARTICLE

"I wanna be your dog": Evaluating the efficacy of univariate and multivariate methods for differentiating domestic and wild canids in North America

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Abstract

The domestic dog (*Canis familiaris*) holds a unique place in human cultures as the first species to be domesticated and has been adapted to a greater diversity of functions requiring far greater morphological variation than any other domesticate. Because of this variability in morphology and pronounced skeletal similarities with other canid species, dog remains are frequently challenging to identify in the archaeological record. Analysts have attempted to overcome these challenges by proposing a diverse array of methods for identifying dog remains. Unfortunately, recent analyses have quantitatively tested and critiqued the effectiveness of several methods widely used for identifying dog remains since the mid-1900s. In addition, many methods were developed specifically for differentiating dogs from their progenitor species, the grey wolf (*Canis lupus*) and analysts working in many regions of the world have frequently assumed, without testing; they will remain effective in differentiating dog remains from other canid species. Using data collected on 538 North American dog, wolf, coyote and fox mandibles, we test the effectiveness of several methods for differentiating dogs from an array of North American canids. Our results reveal that no single method is universally effective and that differentiating dogs from mid-sized canids, like the North American coyote, remains a significant challenge for archaeologists working in North America and likely other parts of the world.

KEYWORDS

canid, dog, domestication, mandibular bowing, tooth crowding, wolf

1 | INTRODUCTION

The domestic dog (*Canis familiaris*) is unique among mammalian domesticates in its extreme morphological variability (Wayne et al., 1997). This diversity presents special challenges for archaeologists seeking to reliably differentiate dog remains from those of morphologically similar wild canids in archaeological assemblages, especially those of similar size. To do so, archaeologists typically follow one of two approaches. First, many analysts employ one, or several, univariate methods focused on the qualitative and/or quantitative characteristics of the canid skeleton (Allen, 1920; Benecke, 1987; Clark, 1996; Clutton-Brock, 1963; Crockford, 1997; Degerbøl, 1961; Grayson, 1988; Lawrence, 1967, 1968; Lupo & Janetski, 1994; Morey & Wiant, 1992; Olsen, 1985; van Wijngaarden-Bakker, 1974, p. 342; Young & Jackson, 1951). Second, some employ multivariate approaches based upon extensive comparative datasets to statistically identify dog and wild canid remains (Elder & Hayden, 1977; Lawrence & Bossert, 1967; Morey, 1986, 1990; Walker & Frison, 1982). Together, univariate and multivariate methods have been key elements in the development of a substantial body of knowledge concerning the origins and domestication of the dog and their dispersion around the world and their role in human cultures (Frantz et al., 2016; Horard-Herbin, Tresset, & Vigne, 2014; Larson et al., 2012; Welker & Byers, 2019). However, both approaches are subject to drawbacks that have yet to be fully explored.

Given the sometimes-difficult task of differentiating dogs from wild canids, we ask the simple question, which methods work best for differentiating various North American canid taxa from one another? The study presented here addresses this important gap in knowledge in two ways. First, we test the efficacy of several univariate methods (tooth crowding, M_1 length and mandibular bowing) widely used in identifying dogs and show that these are not universally successful in differentiating dogs from a selection of wild canids found in North America including wolves (*Canis lupus*), coyotes (*Canis latrans*) and foxes (*Vulpes spp./Urocyon spp*.). Second, we compare the success rates of univariate methods with a multivariate approach. To do so, we compile a large multivariate dataset (Data S1) on canid mandibular morphology which we employ in our own principle component analysis (PCA). Our results reveal that univariate methods can provide a high rate of success depending upon the canid taxa present, but that multivariate methods provide the most effective means of differentiating dogs from the greatest number of canid species, although the effectiveness of multivariate methods are heavily dependent upon the characteristics included.

1.1 | Previous research

Dogs were domesticated by 15,000 years ago in Eurasia and subsequently dispersed around the world alongside human communities (Larson et al., 2012; Leathlobhair et al., 2018; Perri, 2016). Interest in dog domestication, dispersal and the emergence of phenotypically dissimilar breeds has encouraged the development of morphometric tests used to distinguish wild and dogs. These include tooth crowding (Clark, 1996; Clutton-Brock, 1963; Degerbøl, 1961; van Wijngaarden-Bakker, 1974, p. 342), mandibular shape (Drake et al., 2017; Janssens, Miller, & van Dongen, 2016; Lawrence, 1967, 1968; Olsen, 1985), cranial dimensions (Crockford, 1997; Haag, 1948; Phillips, Baxter, & Nussbaumer, 2009; Tourigny et al., 2017), shoulder height (Clark, 1996; Harcourt, 1974), body mass (Losey et al., 2015; Losey, McLachin, Nomokonova, Latham, & Harrington, 2017) and robusticity (De Grossi Mazzorin & Tagliacozzo, 2000) and rely upon a variety of size-based or morphological characteristics. However, many methods used explicitly to differentiate dogs from their wild progenitor, the grey wolf (*C. lupus*), were developed in Europe where wild canids of intermediate size between foxes and wolves are largely absent (except for golden jackals (*Canis aureus*) in the southeast and *Cuon* in the Pleistocene). As a result, some methods rely heavily on the assumption that specimens between wolves and foxes in size are dogs. Though this assumption may be viable in Europe, it is problematic in North America where analysts may reasonably expect to encounter dogs, wolves, coyotes and foxes belonging to several genera within any assemblage. Despite the diversity of North American canid species and the complicated history of dogs in the Americas, few studies have explored the effectiveness of these widely used methods in differentiating dogs from uniquely North American canids.

Tooth crowding has been used to identify dogs since the 1890s (Degerbøl, 1961; Struder, 1901; Wolfgram, 1894). Tooth crowding was believed to result from a shortening of the snout, a trait commonly associated with domesticated animals and linked to neotony, or the conservation of juvenile traits into adulthood which is common in many domesticates (Zeder, 2012). Such data have been collected using methodologies ranging from simple visual evaluations of overlapping teeth (Sablin & Khlopachev, 2002; Germonpré et al., 2009; Germonpré, Lázničková-Galetová, & Sablin, 2012; Germonpré, Lázničková-Galetová, Losey, Räikkönen, & Sablin, 2015; Napierala & Uerpmann, 2012) to various biometric indices calculated for mandibular and maxillary teeth (Benecke, 1987; Degerbøl, 1961, p. 39; Lawrence, 1967; Davis & Valla, 1978; Dimitrijević & Vuković, 2015; Musil, 2000; Lapham, 2010; Struder, 1901; Wolfgram, 1894). As a result, tooth crowding datasets are frequently incomparable with one another. Recently, Ameen et al. (2017) have generated evidence that mandibular tooth crowding is unreliable for differentiating modern dogs from either modern or Pleistocene wolves using refined method that accounts for tooth row curvature.

M_1 length, or mesio-distal diameter, has been used to identify and investigate size change in both New World (Clutton-Brock & Hammond, 1994; Janssens, Perri, Crombé, Van Dongen, & Lawler, 2019; Lapham, 2010; Lupo & Janetski, 1994) and Old World (Dayan, 1994) dogs. M_1 length is less frequently used than tooth crowding but has been used to differentiate dogs from coyotes in the North American Great Basin (Lupo & Janetski, 1994). Tooth length has also been used in generating body mass estimates for canids (Van Valkenburgh, 1990), although reinvestigation has found tooth length to correlate relatively poorly with body mass in dogs and wolves (Losey et al., 2015). Discrepancies between M_1 length and body mass may result from the fact that tooth crowns form before adulthood and are not remodelled over the course of an animal's life (Losey et al., 2015). Notably, Morey (1992) suggests tooth size is unreliable as an indicator of domestication because changes in dental morphology lag behind changes in skeletal structure.

The curvature of the inferior surface of mandibles and shape of the coronoid process have also been used at times to separate wild and domestic canids. As early as 1977, scholars noted that the degree of curvature along the inferior surface of dog mandibles is frequently greater than that found in wolves and coyotes (Olsen, 1985; Olsen & Olsen, 1977). Mandibular bowing has most commonly been applied in a qualitative manner (Olsen, 1985; Olsen & Olsen, 1977), though Drake et al. (2017) have developed and tested a quantitative image-based technique on a sample of dogs and wolves. The curvature of the mandible has been used in the analysis of material recovered from a variety of contexts (Drake et al., 2017; Grayson, 1988; Lawrence, 1967, 1968; Lupo & Janetski, 1994; Olsen, 1985). Other analysts have noted that the coronoid process in dogs frequently curves posteriorly in a manner not found in many wild wolf populations (Olsen & Olsen, 1977), though Janssens et al. (2016) have determined this method to be unreliable.

Multivariate comparisons of North American coyotes, wolves and dogs have proved effective at differentiating wild canids from dogs (Bever, 2005; Elder & Hayden, 1977; Keiser & Groeneveld, 1992; Lawrence & Bossert, 1967; Morey, 1986, 1990; Perea, 2017; Walker & Frison, 1982). Unfortunately, the necessary comparative datasets are labour intensive to produce and have been inconsistent in the characteristics considered. Furthermore, though several comparative datasets have been generated for past studies (Bever, 2005; Elder & Hayden, 1977; Keiser & Groeneveld, 1992; Lawrence & Bossert, 1967; Morey, 1986, 1990; Perea, 2017; Walker & Frison, 1982), they have rarely been made accessible to other analysts. As a result, labour inputs in producing a sufficient dataset often present a significant hurdle to their application.

Although these methods have a long history of use and are used in many regions of the world, their application frequently rests upon the assumption that they are universally effective—an assumption which has received limited formalized study (though see Ameen et al., 2017; Clark, 1996; Drake et al., 2017; Janssens et al., 2019). Additionally, many of the characteristics in use are size-based and may be ineffective where dogs are intermingled with wild canids of similar size. The plasticity of dog morphology and variation found in wild canids makes both assumptions problematic. The following study addresses these methodological issues in an attempt to sort which methods work best for differentiating canid taxa from one another.

2 | MATERIALS

To determine whether any of the widely used methods described above are appropriate means of determining domestic status in archaeological assemblages, morphometric data were collected on modern canid remains of known identity held in university and museum collections in the United States and Canada (MHW and SBM). The sample includes mandibles from modern dogs (n = 61), wolves (n = 186), coyotes (n = 179) and foxes belonging to both the *Vulpes* (n = 59) and *Urocyon* (n = 53) genera (Table 1; Data S1). These specimens belong to collections held by The Pennsylvania State University's Matson Museum, Zooarchaeology Lab and Department of Ecosystem Management (State College, Pennsylvania), the St. Francis Xavier University Biology Department (Antigonish, Nova Scotia), the Field Museum (Chicago, Illinois) and the Santa Barbara Museum of Natural History (Santa Barbara, California).

TABLE 1 Canid taxa represented in this analysis

Common name	Scientific name	# Mandibles
Dog	*Canis familiaris*	61
Wolf	*Canis lupus*	186
Coyote (Western)	*Canis latrans*	64
Coyote (Eastern)	*Canis latrans var.*	115
Foxes (Red)	*Vulpes sp.*	59
Foxes (Grey)	*Urocyon sp.*	53
	Total	538

The dogs used in this analysis include a morphologically diverse array of dog breeds used to evaluate the range of variability present in these animals but are predominantly mesocephalic in skull shape. In addition, samples of both eastern (n = 115) and western (n = 64) coyotes were collected to assess the degree to which morphology impacts the reliability with which these populations can be differentiated from dogs using widely used methods. Eastern coyotes (*C. latrans var*. or *C. latrans* × *Canis lyacaon*) are a hybridized cross between western coyotes from the Plains and eastern wolves from the Great Lakes region (Wheeldon, Patterson, & White, 2010) which are on average 65% larger than western coyotes (Way, 2007) and known to be a morphological intermediate between coyotes and wolves (Kennedy, Leberg, & Baumgardner, 1986; Lawrence & Bossert, 1967; Nowak, 1979). Though hybridized eastern coyotes likely emerged only in the last 100 years following the extirpation of many eastern wolf populations, the expansion of agriculture and the colonization of the region by coyotes from the plains (Kays, Curtis, & Kirchman, 2009), previous work has revealed variability in coyote size since the Pleistocene (Meachen & Samuels, 2012).

3 | METHODS

3.1 | Data collection

Eight linear morphometric dimensions (Figure 1) were collected by the authors on each mandible using Mitutoyo digital calipers. These include the lengths of P_1, P_2, P_3, P_4 following Clark (1996) and the length of M_1 (von den Dreisch, 1976, dimension 13a), the length from the anterior surface of P_1 to the posterior surface of P_4 (von den Dreisch, 1976, dimension 11) and the greatest depth of the mandible (von den Dreisch, 1976, dimension 19). An additional dimension from the anterior surface of P_1 to the posterior surface of M_1 (Figure 2) was collected in order to calculate the bowing index described below. The shape and curvature of the ascending ramus discussed by Olsen and Olsen (1977) and tested on dogs and wolves by Janssens et al. (2016) is not tested here due to the challenges of effectively capturing this characteristic with simple linear measurements. Though it has been asserted that geometric morphometric measurements are more reliable than linear morphometric methods collected using calipers (Ameen et al., 2017; Drake et al., 2017; Mitteroecker & Gunz, 2009; Strauss & Bookstein, 1982), linear methods are a fast and cost-effective means of data collection and are often possible on more fragmentary specimens.

3.2 | Tooth crowding

Mandibular tooth crowding indices were calculated using the formula presented in Clark (1996):

$$\text{Mandibular Tooth Crowding Index} = \frac{P_1 + P_2 + P_3 + P_4}{\text{Length } P_1 \text{ to } P_4}.$$

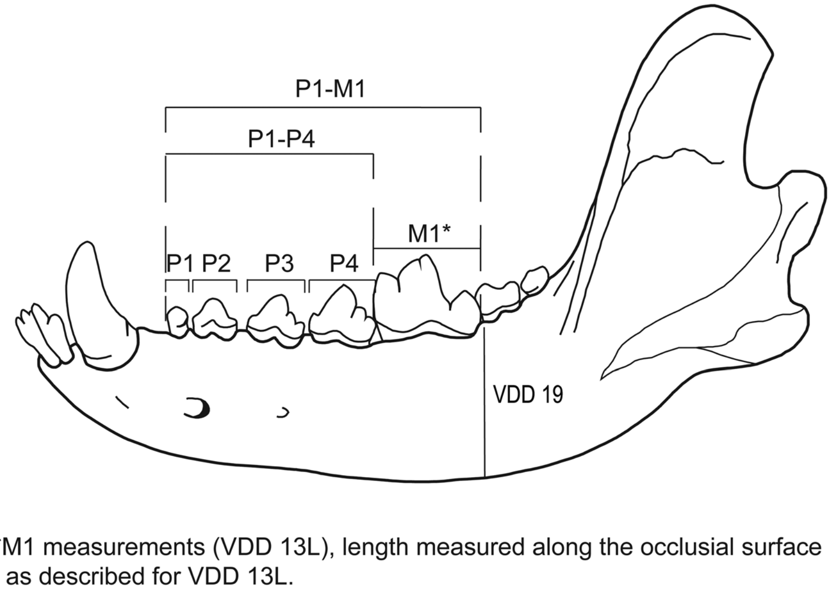

FIGURE 1 A diagram depicting the measurements used in this analysis. *M_1 measurements follow von den Dreisch (1976) 13 L, the length of the first molar measured along the occlusal surface. Figure after von den Dreisch (1976)

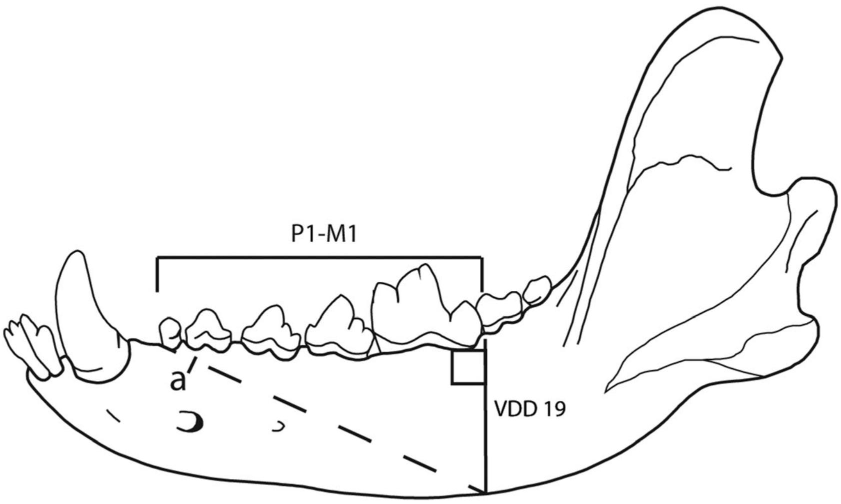

FIGURE 2 Measurements used in calculating the mandibular bowing index (a = the angle used in the mandibular bowing index). Figure after von den Dreisch (1976)

Although Ameen et al. (2017) present an updated method capable of quantifying both crowding and tooth rotation which may also account for overestimation of crowding linked to medio-lateral bowing of the mandible, these methods were not available when data collection was initiated, and we do not address them here.

3.3 | M_1 length

M_1 length was evaluated using von den Dreisch (1976) dimension 13a (Figure 1). An additional 74 measurements on German shepherds were drawn from Janssens et al. (2019).

3.4 | Mandibular bowing

Drake et al. (2017) employed geometric morphometrics to show that mesocephalic dogs exhibit more mandibular curvature than wolves. We develop and test a simplified 'bowing index' based on linear morphometrics and the arctangent function of geometry. Because the angles in a triangle always sum to 180° and can be calculated from length dimensions of the sides, they provide a means of estimating the properties of mandibles. We utilize the length of the mandibular tooth row (P_1-M_1) and the depth of the mandible taken at right angles to the border of the mandible (von den Dreisch, 1976, dimension 19). Together these provide the length of two legs of a triangle placed over the mandible and one angle (Figure 2). This approach overcomes the challenge of allometric scaling by allowing the two length dimensions two vary independently of one another.

3.5 | Testing methodological effectiveness

The effectiveness of methods individually and in concert was evaluated using a combination of ANOVA and MANOVA analysis assisted by a Bonferroni correction (α = 0.008) and a PCA applied to the eight linear dimensions and tooth crowding and mandibular bowing indices for all species and for the dataset limited to dogs, wolves and coyotes using R (Version 3.5.1). The significant range in body size included in these samples, coupled with the extreme value differences between linear dimensions and indices, could over or under value the strength of individual characteristics when considered in a PCA analysis. To overcome these challenges, these data were log transformed for the PCA analysis to equilibrate the effects of size-based metrical data and morphological indexes (e.g., tooth crowding and mandibular bowing). Bonferroni corrections reduce the probability of Type 1 error or the identifying false positives (identifying differences where none exist) in data. Within this context, ANOVA analysis identifies whether statistically significant differences exist between groups tested.

4 | RESULTS

4.1 | Univariate characteristics

A MANOVA analysis applied to the entire dataset reveals statistically significant differences exist between at least one of the taxa represented in this analysis for all variables collected (Table 2). This finding indicates that variability exists within the dataset and that at least one taxa diverges from the rest at each characteristic in question. To further investigate these data, ANOVA analysis supplemented by a Bonferroni correction to reduce Type 1 error was applied to tooth crowding, M_1 length and mandibular bowing calculated as described above.

4.2 | Tooth crowding

ANOVA analysis identified statistically significant differences between at least two of the taxa included in this analysis (α = 0.05, F = 28.011, p < 0.000). Despite these results, substantial overlap between dogs, and wild taxa is clearly present when plotted (Figure 3a). In fact, 18.44% of wolves, 38.26% of eastern coyotes and 40.63% of western coyotes measured fall within the first and third quartiles of the distribution calculated for dogs. ANOVA analysis also reveals that dogs differ significantly from the wolves (α = 0.008, F = 28.011, p < 0.000) and eastern coyotes (α = 0.008, F = 28.011, p < 0.000) in this dataset; however, they do not differ significantly from western coyotes (α = 0.008, F = 28.011, p = 0.999). Eastern and western coyotes differ significantly from one another (α = 0.008, F = 28.011, p < 0.000), with eastern coyotes being statistically similar to wolves (α = 0.008, F = 28.011,

TABLE 2 MANOVA results at α = 0.5

Variable	F	p
P_1	247.7	<0.000
P_2	363.96	<0.000
P_3	682.25	<0.000
P_4	387.86	<0.000
M_1	873.32	<0.000
P_1-P_4	179.03	<0.000
P_1-M_1	770.13	<0.000
Tooth crowding	32.72	<0.000
Mandibular bowing	142.69	<0.000

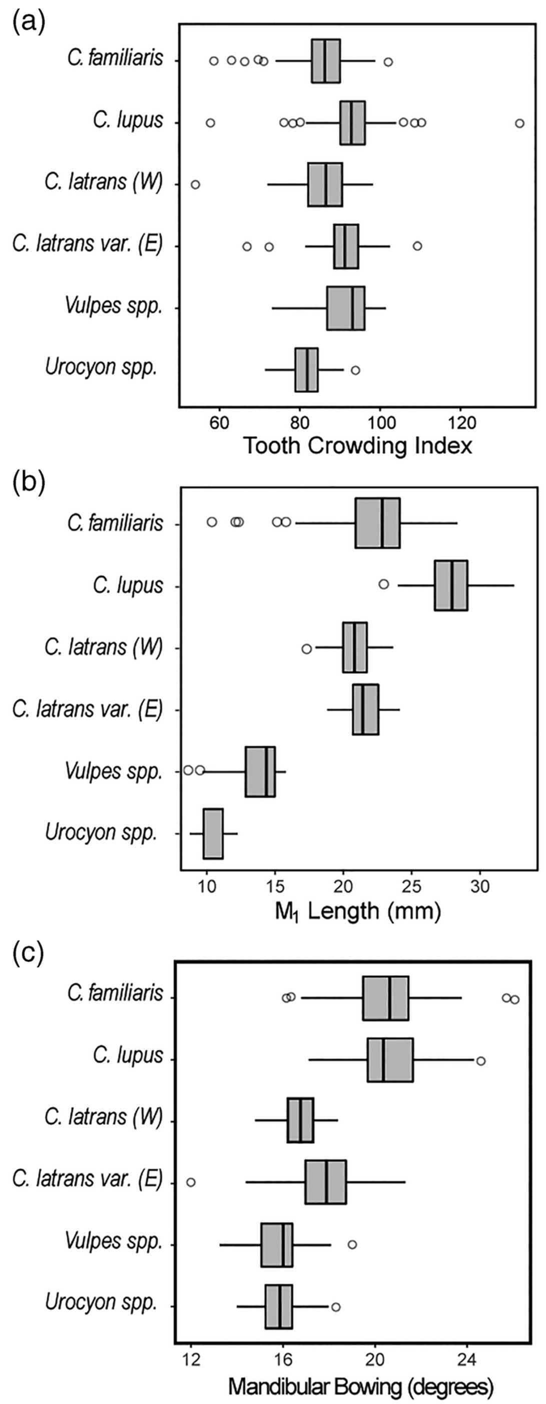

FIGURE 3 (a) Tooth crowding by taxa (following Clark, 1996), (b) M_1 length by taxa following von den Dreisch (1976) dimension 13, (c) mandibular bowing by taxa using the method described above

p = 0.188). Both fox genera are statistically different from dogs (*Vulpes*: α = 0.008, F = 28.011, p < 0.000; *Urocyon*: α = 0.008, F = 28.011, p = 0.003), wolves (*Vulpes*: α = 0.008, F = 28.011, p < 0.000; *Urocyon*: α = 0.008, F = 28.011, p < 0.000), western coyotes (*Vulpes*: α = 0.008, F = 28.011, p < 0.000; *Urocyon*: α = 0.008, F = 28.011, p < 0.000) and one another (α = 0.008, F = 28.011, p = 0.000). Notably, though red foxes are statistically similar to eastern coyotes (α = 0.008, F = 28.011, p = 0.999), grey foxes are not (α = 0.008, F = 28.011, p < 0.000).

4.3 | M_1 length

Univariate plots of M_1 length reveal that dogs are highly variable and, depending upon the breed may overlap with all of the wild taxa sampled in this analysis (Figure 3b). ANOVA analysis reveals that the dogs used in this analysis are significantly different from wolves (α = 0.008, F = 661.70, p < 0.000). Notably, M_1 length is not statistically different between dogs and western coyotes (α = 0.008, F = 661.70, p = 0.122) or between dogs and eastern coyotes (α = 0.008, F = 661.70, p = 1.000). A comparison of eastern and western coyotes reveals no statistically significant differences (α = 0.008, F = 661.70, p = 0.133). Finally, dogs are significantly different from both red (α = 0.008, F = 661.70, p < 0.000) and grey (α = 0.008, F = 661.70, p < 0.000) foxes, which are also statistically different from one another (α = 0.008, F = 661,70, p < 0.000).

4.4 | Mandibular bowing index

ANOVA performed on our mandibular bowing index (Figure 3c) reveals no statistically significant differences between dogs and their closest canid relative the wolf (α = 0.008, F = 142.69, p = 0.953). Statistically significant differences are identified between dogs and eastern (α = 0.008, F = 142.69, p < 0.000) and western coyotes (α = 0.008, F = 142.69, p < 0.000) and both red (α = 0.008, F = 142.69, p < 0.000) and grey (α = 0.008, F = 142.69, p < 0.000) foxes. Notably, eastern and western coyotes are statistically different from one another (α = 0.008, F = 142.69, p < 0.000). Furthermore, though western coyotes are statistically similar to red (α = 0.008, F = 142.69, p = 0.007) and grey (α = 0.008, F = 142.69, p = 0.012) foxes, eastern coyotes are significantly different from both fox genera at p values < 0.000. Red and grey foxes are not statistically different from one another (α = 0.008, F = 142.69, p = 1.000).

4.5 | Multivariate approach

PCA was performed on the log transformed data containing eight morphometric dimensions, the mandibular tooth crowding index, and the mandibular bowing index that reveals distinct overlap between dogs and both western and eastern coyotes. One component accounts for 81.5% of the variability in this sample (Figure 4). All eight linear measurements contribute to this component and are loaded with similar values (between 0.311 and 0.344; Table S1) suggesting that no single linear dimension is more significant than another. Tooth crowding (0.173) and mandibular bowing (0.262) indices have the lowest loading values indicating that they are the least significant contributors to the first component. Tooth crowding is, however, the most significant factor contributing to the second component which explains 9.3% of the variation observed in this sample. When replicating this analysis with only the coyotes, dogs and wolves, PCA again finds overlap between dogs and coyotes. The first component accounts for only 70.2% of the variation in this sample (Figure 5). M_1 length (0.365) and the length of the tooth row from P_1 to M_1 (0.360) are the most strongly loaded variables of the first component. All other linear measurements exhibit loadings of between 0.272 and 0.358 (Table S2). Mandibular bowing and tooth crowding again have the weakest loadings at 0.152 and 0.237, respectively.

Given that this PCA analysis primarily relied upon a variables determined by existing methods developed explicitly to differentiate dogs from wolves in which size plays an important role, the residual effects of size in these results are not surprising. PCA differentiates dogs of various breeds from wild canids with between 70% and 80% of the variability in these comparisons explained by a single component when all of the taxa in this analysis are included, but is less successful when limited to coyotes, dogs and wolves. In both PCA analyses, the first principle component was most strongly influenced by linear measurements, especially the length of M_1 and length of the tooth row (P_1-M_1), suggesting that size is a significant factor in the success or failure of methods based upon the characteristics tested here.

These results should, serve as a cautionary tale. Multivariate methods like PCA have been proven effective in differentiating various canid taxa (Bever, 2005; Elder & Hayden, 1977; Keiser & Groeneveld, 1992; Lawrence & Bossert, 1967; Morey, 1986, 1990; Perea, 2017; Walker & Frison, 1982); however, their success is determined by the characteristics included in the dataset. We relied primarily on the linear measurements and indices underlying several existing methods used in identifying dog remains in archaeological assemblages. These have commonly been developed specifically to differentiate dogs from wolves, a comparison in which size is often a reliable factor. Analysts working in environments populated by wild and domestic canids of similar size should be aware that these methods may be less effective in differentiating dogs from other canids more similar in size. A clear example of this is the overlap between western and eastern coyotes and dogs in these analyses. PCA based upon all of the characteristics and taxa (first PCA analysis) places 90.32% of western and 67.26% of eastern coyotes into the 95% confidence ellipse assigned to dogs (Table 3), while placing 27.66% and 40.42% of dogs into the western and eastern coyotes' ellipses. This PCA also experienced difficulties separating eastern and western coyotes from one another. As shown by other multivariate analyses (Bever, 2005; Elder & Hayden, 1977; Keiser & Groeneveld, 1992; Lawrence &

FIGURE 4 The results of a principal component analysis performed on all of the data available for each taxon. Ellipses represent 95% confidence intervals around each taxon

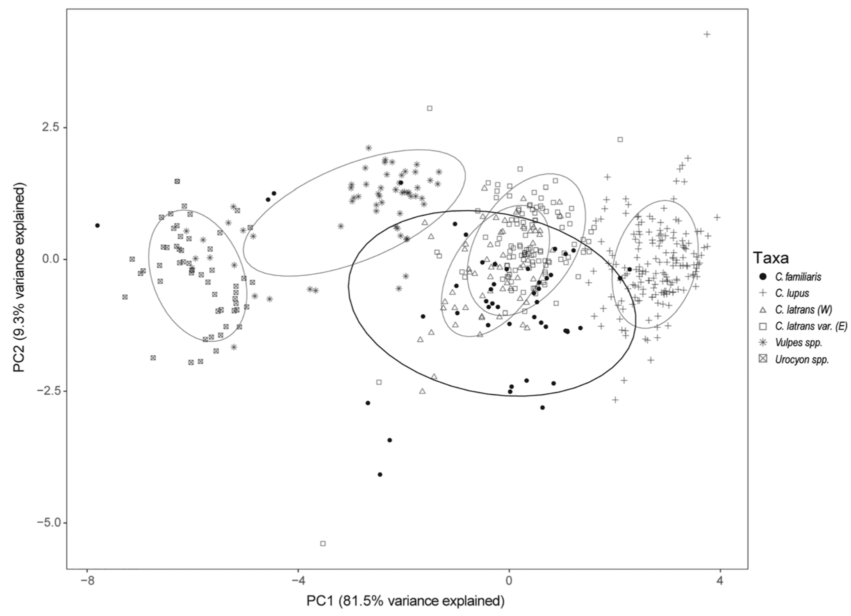

FIGURE 5 The results of a principal component analysis applied to only the dogs, wolves, and coyotes in the dataset. Ellipses represent 95% confidence intervals for each taxon

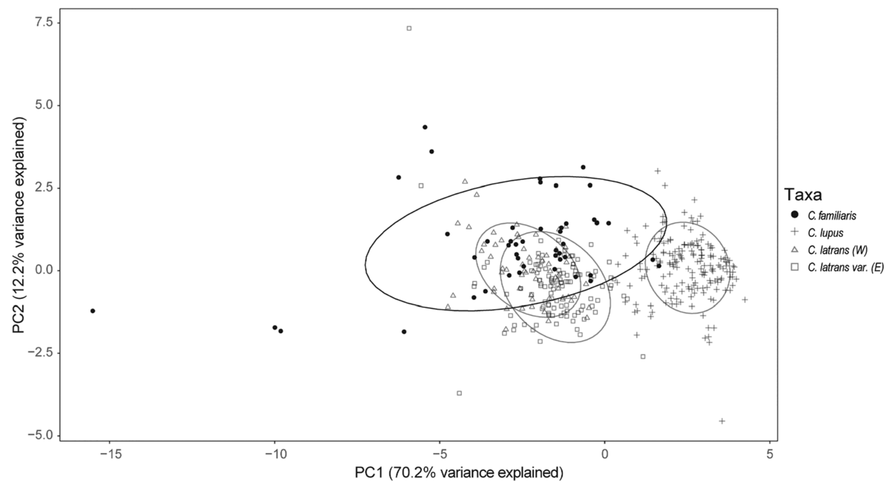

TABLE 3 The percent of each species falling into another species 95% confidence ellipse in the principle component analysis (PCA) of all species

	Dog (*Canis familiaris*)	Wolf (*Canis lupus*)	Western Coyote (*Canis latrans*)	Eastern Coyote (*Canis latrans var.*)	Red Fox (*Vulpes sp.*)	Grey Fox (*Urocyon sp.*)
Dog		1.14	27.66	40.43	1.67	0.00
Wolf	9.71		0.000	0.000	0.000	0.00
Western	90.32	0.000		64.52	0.000	0.00
Eastern	67.26	0.000	53.10		0.000	0.00
Red	11.67	0.000	0.000	0.000		10.00
Grey	0.000	0.000	0.000	0.000	0.000	
Effectiveness[a]		98.86	72.34	59.57	98.33	100.00

[a]Calculated as 100% dogs falling into another taxons ellipse.

Bossert, 1967; Morey, 1986, 1990; Perea, 2017; Walker & Frison, 1982), it is probable that a PCA based on other less size-dependent variables would prove more successful.

5 | DISCUSSION

Scholars have relied upon a variety of methods in identifying domestic dog remains in archaeological assemblages; however, the development of these methods has been driven heavily by the desire to differentiate domestic dogs from their progenitor, the grey wolf. Many existing methods were developed by scholars working on archaeological material from European environments where few mid-sized canid species existed. As a result, few other species needed to be considered, and size proved to be an effective means of differentiating dogs from wolves. Reliance upon size is certainly viable under these conditions; however, scholars should not assume that these methods are universally successful in differentiating dogs from all other wild canids, especially those more similar in size to domestic dogs. Our results demonstrate that tooth crowding, M_1 length and mandibular bowing are not universally effective in differentiating dogs from wolves, coyotes and foxes, all species which occur regularly in North American assemblages. The differentiation between dogs and coyotes which are very similar in size and physical proportions is particularly challenging. As a result, we suggest the reliability of these, and other, methods needs to be tested before analysts use them to differentiate dogs from wild canids in North America or other canid taxa elsewhere in the world. We provide a test of several methods in this analysis and present a new method for quantifying mandibular curvature, a characteristic which has been unsystematically used in differentiating dogs from coyotes (Grayson, 1988; Lawrence, 1967, 1968; Lupo & Janetski, 1994; Olsen, 1985) and which Drake et al. (2017) have shown has promise as a means for differentiating modern dogs from wolves.

As reported by Ameen et al. (2017), we find that mandibular crowding indices are unreliable as a means of differentiating dogs from wolves; however, we build on their results by including coyotes and foxes. Although our data reveal statistically significant differences between dogs and wolves, they do not between dogs and coyotes and some foxes. M_1 length and mandibular bowing calculated following our method appear more effective in differentiating dogs from some, but not all, of the other canid species tested. M_1 length is most effective in differentiating dogs from wolves and foxes. Importantly, the M_1 length exhibited in the sample of North American wolves used here is nearly identical to that reported for modern and Pleistocene Eurasian wolf populations (Benecke, 1987; Bökönyi, 1975; Dimitrijević & Vuković, 2015; Germonpré, Sablin, et al., 2015; Janssens et al., 2019; Musil, 2000). Mandibular bowing indexes calculated using our method appear most effective in differentiating dogs from coyotes and foxes. Our finding that mandibular bowing is not statistically significant as a means of differentiating dogs from wolves should not be taken as a contradiction of Drake et al. (2017), since our methods differ from theirs. Drake et al.'s (2017) method captures the overall shape of the mandible and may be more sensitive to the specific characteristics of dog and wolf mandibles. Furthermore, Drake et al. (2017) included a more extensive sampling of brachycephalic and dolichocephalic breeds than our analysis. Our method did, however, prove more successful than M_1 length in separating dogs from coyotes, and demonstrates promise in separating small dogs from fox species. By testing the effectiveness of M_1 length, tooth crowding and mandibular bowing as methods for separating dogs from wolves, but also coyotes and foxes, we reveal species specific differences in methodological reliability. Table 4 reports the effectiveness of each method tested here as the percentage of each taxon which do not fall into the 95% confidence interval of another taxa. When employed in concert, these measures may enable analysts to draw upon the strengths of each method to improve their ability to identify and study canids in the past (Janssens et al., 2019). For example, a bivariate plot of M_1 length and mandibular bowing results in good separation between dogs and many North American canids (Figure 6).

PCA applied to our dataset of eight linear measurements and the tooth crowding and mandibular bowing index proved less effective than other similar multivariate analyses (Bever, 2005; Elder & Hayden, 1977; Keiser & Groeneveld, 1992; Lawrence & Bossert, 1967; Morey, 1986, 1990; Perea, 2017; Walker & Frison, 1982). Over 80% of the variability in these samples explained by a single component, and despite attempts to limit the influence of size in this analysis, linear measurements, especially the length of M_1 and length of the tooth row (P_1-M_1), remain far more influential in this PCA analysis than either tooth crowding or mandibular bowing. When limited to coyotes, wolves and dogs,

TABLE 4 Effectiveness in distinguishing dog (*Canis familiaris*) from other canids by method

Method	Grey Wolf (*Canis lupus*)	Western Coyote (*Canis latrans*)	Eastern Coyote (*Canis latrans* var.)	Red, Arctic, Kit foxes (*Vulpes sp.*)	Grey or Island foxes (*Urocyon sp.*)
Tooth crowding	High (81.56%)	Moderate (59.38%)	Moderate (61.74%)	High (79.37%)	Moderate (66.04%)
M_1 length	High (100.00%)	Moderate (62.50%)	Moderate (67.83%)	High (100.00%)	High (100.00%)
Mandibular bowing	Moderate (47.43%)	High (100.00%)	High (94.69%)	High (100.00%)	High (100.00%)
Principal component analysis	High (98.86%)	Moderate (72.34%)	Moderate (59.57%)	High (98.33%)	High (100.00%)

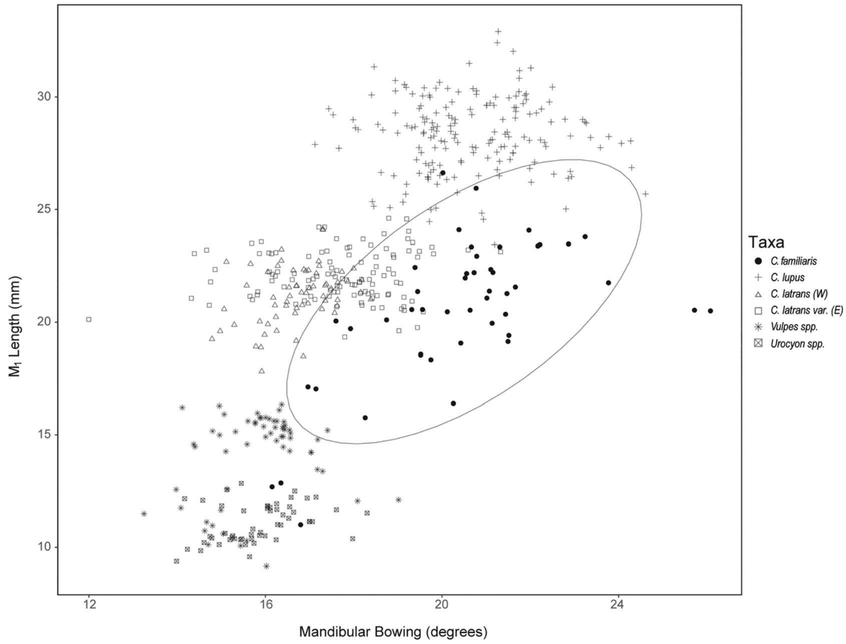

FIGURE 6 Canid taxa plotted by M_1 length and mandibular bowing revealing separation between domestic dogs and other canids (ellipse represents a 95% CI for the domestic dogs included in this analysis)

component one, which is again strongly influenced by linear measurements including tooth size, accounts for over 70% of the variation and over 90% of western coyotes and 67% of eastern coyotes into the 95% confidence ellipse calculated for dogs. The success of PCA and related methods in other published analyses (Bever, 2005; Elder & Hayden, 1977; Keiser & Groeneveld, 1992; Lawrence & Bossert, 1967; Morey, 1986, 1990; Perea, 2017; Walker & Frison, 1982) demonstrates that effectiveness of our application was limited by the dataset, specifically, the linear dimensions used in testing other existing methods.

Together, these findings support the idea size differences are important to the success of some existing methods for differentiating dogs from wild canids. This means these methods may be ineffective when applied to contexts where dogs and wild canids are similar in size and proportions, like those in North America. Notably, our results also reveal differences between eastern and western coyotes which highlight the former's hybrid nature (Kennedy et al., 1986; Lawrence & Bossert, 1967; Nowak, 1979; Wheeldon et al., 2010), while also revealing that the evolutionary history of canid populations may impact the reliability of methods on a more regional level than has been assumed. Though the impacts of regional or evolutionary changes may be less significant, future analyses may find it useful to consider these when developing and testing methods for differentiating canid taxa.

6 | CONCLUDING REMARKS

Though a number of characteristics have been used in identifying dog remains recovered from archaeological sites, relatively few analyses have systematically tested the reliability of the characteristics presented here in differentiating dogs and wolves from other canid species. This analysis provides a test of tooth crowding, M_1 length and mandibular bowing in dogs and North American wolves, coyotes and foxes as discriminatory methods. Our results support assertions made by Ameen et al. (2017) that tooth crowding is not reliable as a means for confidently identifying dog remains in archaeological contexts. M_1 length and mandibular bowing are found to more reliably distinguish dogs, though the reliability of both methods varies depending upon the canid species in question. Given these results, we suggest that relying on any single characteristic is inadvisable, and that even two characteristics (e.g., M_1 length and mandibular bowing) provides a much superior test of species identification. These results indicate that future studies are needed to test the reliability of methods used in identifying dogs in North America and other regions of the world where numerous canid species are found.

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