CROCODILE TALK: STRUCTURAL ANALYSIS OF AMERICAN AND MORELET'S CROCODILE VOCALIZATIONS IN BELIZE

BY
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ABSTRACT

Out of the extant reptilians, crocodilians are the most vocal (Vergne et al, 2009). Crocodiles use vocalizations for social interactions, such as courting and territorial defense (Vergne et al, 2012), as well as distress or threat calls (Boucher et al, 2020). There are two types of crocodiles living in Belize, the American crocodile (*Crocodylus acutus*) and the Morelet's crocodile (*Crocodylus moreletii*), and they have been hypothesized to interbreed based on genetic evidence and morphological traits of both species being exhibited in individuals (Ray et al, 2004). The overall aim of this project was to analyze the structure of calls made by both American crocodiles and Morelet's crocodiles and to analyze any differences between the calls made by both species. Crocodiles were temporarily captured and restrained during ongoing capture surveys, and any vocalizations made during capture were recorded. Morphometric data was also collected during this time. Afterward, each recording underwent acoustic analysis in RavenPro to determine the sound structure of each call.

This was done by collecting data with the following parameters: total duration (DT), duration of the first quartile ($D_{1/4}$), max frequency (F_{max}), beginning frequency (Beginning), the frequency at the first quartile ($F_{1/4}$), end frequency (F_{end}), the slope of the first quartile (Slope 1), and slope of the remaining three quartiles (Slope 2). The call structures were then compared between species, age classes, and individuals. No clear species or age class difference was observed. However, there was great variation found amongst the seven individual crocodiles analyzed, suggesting that these vocalizations are more complex than previously thought and possibly individually distinct.

Dr. Athena Rycyk

Natural Sciences

Introduction

Water covers over 70% of the Earth's surface, containing many different ecosystems and organisms. However, aquatic and marine biodiversity is at risk due to many anthropogenic factors (Jefferson et al, 2021). These areas provide complex ecosystem services and the organisms living there are vital to maintain a good overall ecosystem health. Crocodilians are typically considered apex predators and play a key role in controlling prey populations and are considered ecosystem engineers by manipulating their environment, creating suitable habitat for a large variety of other animals (Somaweera et al, 2020).

Crocodile Biology

Out of the extant reptilians, crocodilians are the most vocal (Vergne et al, 2009). They use vocalizations for social interactions such as courting and territorial defense (Vergne et al, 2012), as well as distress or threat calls (Boucher et al, 2020). The process of sound production in crocodilians is not well understood. However, evidence suggests that air is pushed through the glottis, using surrounding muscles to vary tension for pitch and duration control (Vergne et al, 2009). Crocodilians are semi-aquatic, carnivorous reptiles. Their bodies are well adapted to spend a large portion of their day in water, including their great buoyancy control with inflating or deflating their lungs (Grigg, 2015). In their throat, there is a palatal flap, which closes so they can regulate water intake when not actively swallowing. They are excellent swimmers with a laterally compressed tail and webbed hind feet (Grigg, 2015).

Their eyes, ears, and nostrils are high on their heads, allowing them to be almost fully submerged while still having their visual, olfactory, and auditory senses intact. Also, their nostrils and ears can be easily sealed, along with their eyes using a nictitating membrane, which is a clear third eyelid that protects the eye without blocking vision when the animal is completely under the water (Grigg, 2015). Crocodile eyes also have a tapetum lucidum, a mirror-like structure that is used to maximize the amount of light that is being absorbed by photoreceptors. It is found within the retinal pigment epithelium (Schwab et al, 2002). When a spotlight is shined during a nocturnal survey on a crocodile, the tapetum lucidum reflects back a reddish color, indicating that there is a crocodile there (Figure 1).



Figure 1: American-Morelet's Hybrid crocodile with red-eye shine. The photo was taken in November of 2022 in Hopkins, Belize by Jonathan Triminio.

Morelet's and American Crocodiles

The clade "Crocodylia" has been around for about 100 million years, with three extant families. Of the three, crocodiles belong to the family Crocodylidae (Grigg, 2015). Out of the 14 true crocodile species, there are two types of crocodiles living in Belize, the American crocodile (*Crocodylus acutus*) and the Morelet's crocodile (*Crocodylus moreletii*).

The American Crocodile is the most widely distributed New World crocodile, with its northern extent of its range starting in the southern tip of Florida, extending down into Mexico, Central American countries, Caribbean countries, as well as a few northern countries in South America. Overall, the American crocodile is found in 18 countries (Thorbjarnarson, (n.d.)). The species is currently listed as vulnerable (IUCN, 2022), with its main threats being habitat loss or degradation, hunting, and hybridization with other species of closely related crocodiles. There was a great decline in populations between the 1930's and 1970's because of commercial overexploitation, but a lot of populations have started to stabilize. They are typically found in brackish water along coastlines, but have been reported in freshwater systems, such as rivers and lakes as well (Thorbjarnarson, (n.d.)).

The American Crocodile is considered a larger species, with males reaching anywhere between five to six meters and females between three and three and a half (Thorbjarnarson, (n.d.)).

American crocodiles are known to make hole and mound nests, with nesting season in the dryer parts of the year (typically March to May). Hatchling season coincides typically with wet or rainy season usually running from late June to mid-July (Platt and Thorbjarnarson, 2000b). Nesting sites are often reused yearly since adequate nesting habitat is limited. Suitable nesting habitat typically consists of elevated beach ridges that are near shallow lagoons, which provide protection to hatchlings from waves and a gentler salinity (fresh or brackish water) (Platt and Thorbjarnarson, 2000a).

The Morelet's Crocodile is found in Mexico, Belize, and Guatemala (Figure 2). It is currently listed as Least Concern/Conservation Dependent on the IUCN red list (IUCN, 2022). The major threats to the Morelet's crocodile are illegal hunting and habitat loss or destruction. There was a significant decrease in population counts during the 1940's and 1950's due to unregulated skin hunting (Álvarez del Toro, 1974). However, they are considered to be common in Belize currently (Platt et al, 2008).

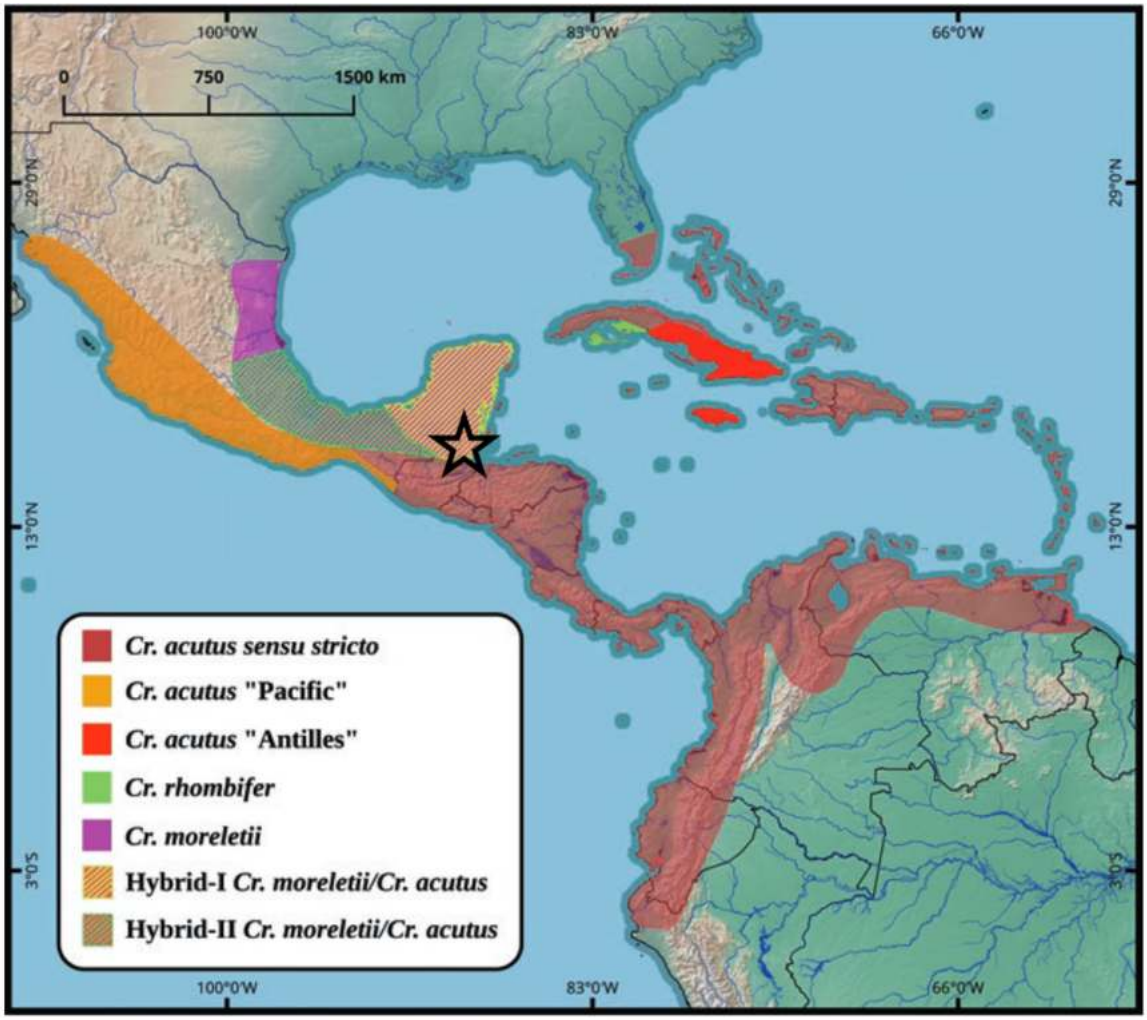


Figure 2: This is a map showing the distribution of some crocodiles, including the Morelet's (*Cr. moreletii)* and American (*Cr. acutus*), taken from *Conservation Genetics of New World Crocodilians* chapter 4 (Zucoloto et al, 2021). The black star is where Belize is located, where both species are found, along with hybrids.

The Morelet's is considered medium-sized with adult males reaching lengths of up to 4.5 meters. They typically have a broad snout, weakly keeled osteoderms on their dorsums, as well as irregular scale groups on their tails (Platt and Rainwater, 2005).

These crocodiles are typically found in freshwater, such as marshes, swamps, ponds, rivers, lagoons, and man-made bodies of water (Álvarez del Toro and Sigler, 2001; Escobedo-Galvan et al, 2008). However, have been observed in brackish or saline environments as well (Platt et al, 2008).

Female Morelet's typically reach maturity in seven to eight years, when they are about one and a half meters in length. They are mound nesters, and their clutch size is between 20 and 50 eggs, which are laid at the end of the dry season (Mid-May to July). The hatching season coincides with the peak of the wet season (August to September) (Álvarez del Toro, 1974; Perez-Higareda, 1980; Platt, 2008). The females open the nests and carry the hatchlings in their mouths to transport them to the water (Álvarez del Toro, 1974).

The two sympatric species (Figure 2) can be distinguished by some key features including size, scale pattern, etc. The head of the American crocodile is typically long and narrow with a more prominent pre-orbital hump, while the head of a Morelet's is shorter and wider. The dorsal scute pattern is irregular on the American, but not on the Morelet's.

In contrast, the Morelet's croc has irregular subcaudal scute groups where the American typically has straight rows (Figure 3).



Figure 3: Left image of American Crocodile's straight subcaudal scute groups. Right image of Morelet's Crocodile's irregular subcaudal scute groups. Both images were taken by Helena Wood-Barron in the summer of 2022 in Belize.

Belize

Belize is the second smallest country in Central America with 22,963 km^2 of land. It is located at 15°52' and 18°30' North Latitude and 87°28' and 89°14' West. The longer portion is 280 km from North to South, all on the coast. It is 110 km in width (Young, 2008). There are 16 major watersheds in Belize (Coastal Zone Management Authority & Institute, 2014). The northern lowlands of the country have a lot of freshwater rivers, lagoons, wetlands, and swamps, while coastal areas are mostly lagoons and mangrove habitats. Currently, 26.2% of Belizean national territory is protected by law.

The main threats to Belize's ecosystems are high rates of deforestation, poor waste-management, and coastal development. Belize's deforestation rate is twice that of the rest of Central America's, posing a serious threat to wildlife (Young, 2008). Improper waste management leads to highly polluted areas, including waterways. Coastal development is especially a problem for the resident crocodiles because it destroys suitable nesting and hatchling habitat, like elevated beach ridges. It also introduces pollutants such as heavy metals into the water (Coastal Zone Management Authority & Institute, 2014). Climate change, like most places, is another big threat to Belize because of rising sea levels and sea temperatures (Young, 2008).

Hybridization

The two species of crocodiles in Belize often are found in overlapping areas along the Southern Coast, such as in Placencia, Sennis, Monkey River (Triminio, J., personal communication, 2022), and have been known to interbreed (Muniz et al, 2021). Hybridization between American and Morelet's crocodiles has been hypothesized based on genetic evidence and morphological traits of both species being exhibited in individuals (Ray et al, 2004). According to Hekkala et al (2015), hybridization in Belize is typically between male *C. moreletii* and female *C. acutus*, likely due to male Morelet's establishing territory and mating with female Americans at the end of American crocodile breeding season. Hybrids in this specific study were exclusively found in freshwater areas (Hekkala et al, 2015), which could disrupt saline ecosystems if there are fewer crocodiles there.

The increase in hybridization can lead to the decline of the pure-bred populations. Although hybridization is a naturally occurring phenomenon, anthropogenic factors have escalated the rate of how often these hybridizations occur. Interbreeding is more prevalent now where species were separated in the past, as physical barriers, such as densely forested areas, have been removed. Hybridization is a major threat to the Morelet's crocodile because eventually the hybrids will displace the original parental species (González-Trujillo et al, 2012). There are not clear policy guidelines regarding hybrids under the U.S. Endangered Species Act (Allendorf et al, 2004).

Sound Analysis and Acoustic Monitoring: Why They Matter

Acoustic monitoring uses sounds produced by a species to detect its presence. Recorders are placed in the field and utilized for a long period of time. The recordings are then analyzed for any known sounds, such as specific calls made by an animal. There are many benefits to using passive acoustic monitoring (PAM) for conservation, such as using recordings to estimate species presence and abundance, population density, and different community compositions, as well as monitoring spatial and temporal trends in species (Browning et al, 2017). Within the last few decades, the automatic detection of animal sounds has become more developed and common (Thomas and Marques, 2012). A lot of current PAM research focuses on marine mammals, anurans, bats, and birds (Thomas and Marques, 2012; Sugai et al, 2019; Pérez-Granados and Traba, 2021), but there is little done with reptiles, especially crocodilians specifically.

A possible application of characterizing species-specific vocal cues in the American and Morelet's crocodiles is using PAM to better understand the distribution of both species and these new hybrids (Staniewicz, 2019). Using PAM, animal densities can be estimated in areas that are hard to access and can also be done in poor weather conditions. Auditory signals typically also travel a greater distance than visual cues. Characterizing the structure of vocalizations for each species will allow for researchers to correctly identify crocodile species and also calculate species abundance using a supported cue rate (average calls per unit of time) to translate the number of detected calls into the number of crocodiles (Marques et al, 2013). Such monitoring is a noninvasive method to detect the presence of these vocal species with many advantages such as being able to sample simultaneously at multiple locations, around the clock, and over long periods of time. Acoustic monitoring could detect changes in the distribution of crocodiles because of habitat loss, illegal hunting, or being displaced by another species or hybrid (Thorbjarnarson, 2010).

A better understanding of structural differences in vocalizations or similarities could provide insight into possible vocal misidentification between species that has led to hybridization. In some songbirds, females will typically respond more to songs found in their local area versus foreign songs from neighboring populations (Searcy, 1990; and Searcy et al, 1981). Although there is little research on the crocodile mating process, it is possible that female crocodiles will also prefer familiar calls versus calls of a foreign structure. In anurans, females are better at call differentiations, therefore less susceptible to vocal misidentification than males.

It is more costly for females to mate with the wrong species or mate with a poor-quality male, though it is possible, so females tend to be more selective with their mates (Bernal et al, 2009).

Goals of the Study

There is some vocalization research on the American crocodile (Boucher et al, 2020), however, there is little known about the Morelet's call structure. This research will provide a better understanding of vocalization structure in the American Crocodile, the Morelet's Crocodile, and American-Morelet's hybrids that can be used 1) to understand differences in vocalizations of these species and the hybrids and 2) to implement passive acoustic monitoring distribution surveys. In addition to looking at differences between species, differences between individuals were also examined.

Methods

Study Area

The study area for this project was on the Eastern coast of Belize in five different sites (Figure 4). American, Morelet's, and American-Morelet's hybrid crocodiles were caught from a boat during capture surveys in the month of August in 2022. There were 10 surveys done, some areas chosen had single or multiple surveys, such as in Belize city (three surveys). The areas that contained more than one survey were typically far from Placencia, CRC's headquarters, and required overnight stays.

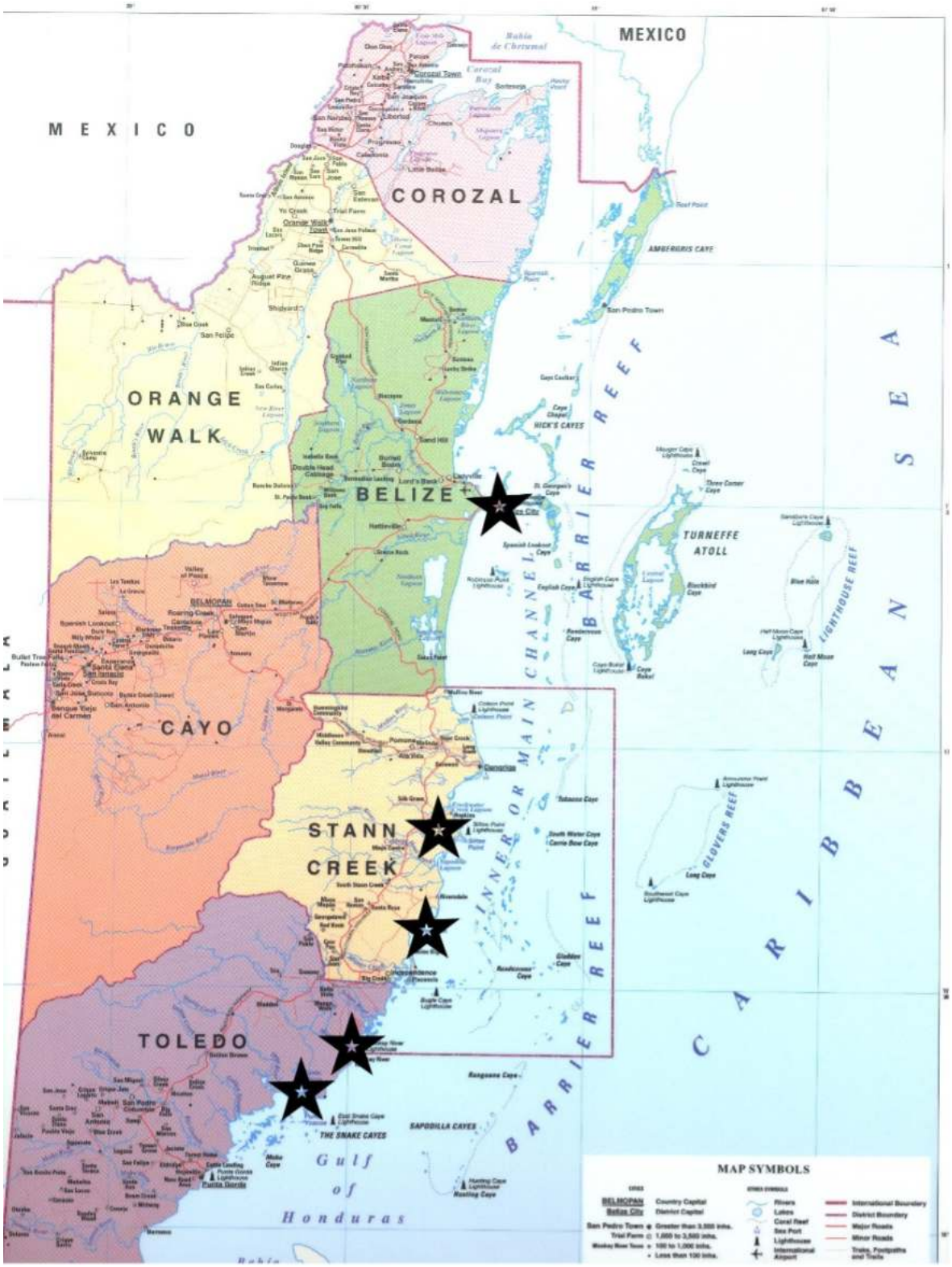


Figure 4: Map of Belize (Belize Map). Black stars are used to indicate where surveys were done.

Capture Survey Methods

Capture surveys were conducted following safe capture and examination practices developed by Sánchez Herrera et al (2011). Surveys occurred on a motorboat shortly (15-30 minutes) after sunset. Crocodiles were spotted by shining a spotlight and looking for any red eyeshine. If a crocodile was spotted, it was caught and brought on board, or land if it was an adult. Crocodiles were captured by hand or with catchpole snares depending on their size. If any vocalizations occurred during the capture and restraint, they were recorded for approximately one to three minutes using the AVR X application on an iPhone 11 with the settings set to as follows: WAV file format, High encode quality, sample rate of 48,000Hz, bitrate at 320kbps, and a Mono channel. The microphone was held approximately 1-2 m away from larger subadult and adult crocodiles for safety, but smaller subadults, juveniles and hatchlings were handheld, and the microphone was about 50 cm away (Boucher et al, 2020).

Following the acoustic recording, the crocodile was restrained with electrical tape around its snout, not obstructing nostrils, or over eyes for small hatchlings. If the crocodile was longer than 120 cm, there was a damp cloth also taped around its eyes to relieve stress and reduce movement. Hatchling, juvenile, and smaller subadults were restrained by hand and arms, under the forelimbs and at the base of the tail (Figure 5). Larger animals were gently sat on, typically near the front section of the body.



Figure 5: (A) Restraining a smaller subadult Morelet's crocodile during vocalization recording. (B) Restraining an American hatchling crocodile during morphometric measurements. (C) Restraining an adult Morelet's crocodile. All taken in BZ, August 2022 by Jonathan Triminio.

Another researcher would restrain the tail and hind legs by pinning them against the body. Following the restraint, another researcher obtained the following morphometric data: head length; snout length; pre-orbital length; pre-orbital width; cranial width; maxillary width; premaxillary width; total length; snout–vent length; tail width; right hind foot length; and sex.

They were also categorized by their size (Table 1) as well as possible species identification. If traits of both species (American and Morelet's) were present within one individual, it was categorized as a hybrid. Pictures of nuchal scute and tail patterns were taken for possible future examination. We also examined individuals for health and the presence of external parasites.

Table 1: This table shows the size grouping category for the American and Morelet's Crocodile. Taken from Crocodile Population Survey Methods manual (Tellez).

	American Crocodile	**Morelet's Crocodile**
Hatchling	< 50cm	< 50cm
Juvenile	51cm-120cm	51-100cm
Subadult	121cm-180cm	101cm-150cm
Adult	181-240cm	151cm-200cm
Large Adult	> 241cm	> 201cm

In addition to physiological data of the crocodile, environmental data of the collection site including average air and water temperatures, salinity, and pH, were recorded using a thermometer, refractometer, and pH meter respectively. After collecting the data, crocodiles were marked via scute clipping with a unique numerical code following the methods of Sánchez Herrera et al (2011) for future identification, where each scute is given a number based on position (double right: hundreds, double left: tens, or single row: singles). Each region has a unique numerical coding system that will identify the region the crocodile was captured. Once all data are collected, crocodiles were released at the site of capture.

Sound Analysis

After traveling back to the United States, the recordings were analyzed, and low-quality calls were filtered out and not included in analysis. These low-quality files included any with heavy background sound interference and talking or movement noise. This was done by an aural and visual inspection of the spectrograms in RavenPro. To standardize analysis, only seven calls were selected from each individual. Through preliminary analysis and comparison with similar studies, the number seven was chosen because it was the highest number that would allow for the majority of the individuals to be included. Individual files that did not have at least seven clear calls were also not included in analysis. The first usable seven calls with clear spectrograms that contained little to no interference from undesired sounds in the file were selected for analysis. Any clear outliers were not included in analysis. With RavenPro, the calls were isolated using the waveform by looking at where the call started and ended temporally. After isolation, the calls were analyzed using built-in tools to measure the parameters, listed in the table below (Table 2). They were stored in a txt file using the selection table feature in RavenPro.

Table 2: This table describes the measurements used in the selection tables. Descriptions taken from the Raven Pro 1.4 User's Manual (Charif et al, 2010).

Selected Measurement	Description
Begin Time	Time in seconds where selection starts
Low Frequency	The selection's lowest frequency bound

Delta Time	Change in time in seconds
Max Frequency	The point on the spectrogram with maximum pressure
Peak Frequency	The frequency with peak power
Center Frequency	The frequency where each half of the frequency sections have equal energy
Peak Time	Time where peak amplitude occurs
Peak Frequency Average Contour Slope	Average slope of Peak Frequency Contour
Peak Frequency Maximum Contour Slope	The maximum slope of Peak Frequency Contour
End Time	Time in seconds where selection ends
High Frequency	The selection's highest frequency bound
Frequency 25%	The frequency 25% of the way into the selection
Time 25%	Duration of the first quartile
Bandwidth 90%	Subtraction of 95% and 5% frequencies
Delta Frequency	Change in frequency
Peak Frequency Contour Slope	Slope of peak frequency measurements between selection slices
Peak Frequency Minimum Contour Slope	The minimum slope of Peak Frequency Contour

After creating the selection tables, all vocalization boundaries (start and end time) and measurements underwent manual verification. This process involved examining each vocalization to ensure that the automatically-measured values were correct. If a peak frequency measurement was found to be triggered by background noise and not the vocalization, the background noise was filtered out and the measurement was repeated. After each measurement was verified, the selection tables were saved and then opened as Excel files. The data were grouped by species and age class.

Further analysis required segmenting each vocalization into 0.005 second segments, and the peak frequency of each slice was calculated with RavenPro. The first slice was used for the beginning frequency and the last slice was used as the end frequency. The max frequency was also calculated using these segmented slices (Figure 6).

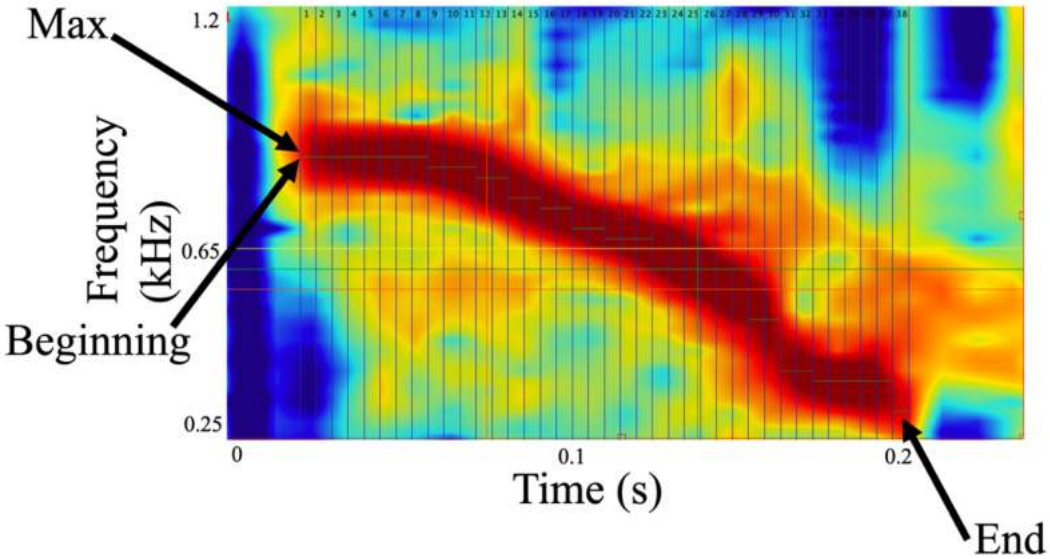


Figure 6: Spectrogram of a vocalization made by a Morelet's juvenile crocodile created in RavenPro. Selections are 0.005 seconds long, with the peak frequency of each slice being the green horizontal bar. Arrows indicating the beginning, max, and end frequencies are labeled as such.

The data, including total duration, first quartile duration, maximum frequency, and first quartile frequency, which were all calculated using selection table measurements, were organized into a separate Excel sheet. The slope of the first quartile (Slope 1) was calculated with equation 1,

$$Slope\ 1 = (F_{\frac{1}{4}} - F_{max})/D_{\frac{1}{4}} \qquad \text{Equation 1}$$

where $F_{1/4}$ is the frequency at the first quartile and F_{max} is the maximum frequency. $D_{1/4}$ is the duration of the first quartile.

The second slope (Slope 2) was calculated with equation 2,

$$\text{Slope 2} = (F_{end} - F_{\frac{1}{4}})/\ (DT\ -\ D_{1/4}) \qquad \text{Equation 2}$$

where F_{end} is the end frequency, and DT is the total duration (Boucher et al, 2020).

Statistical Analysis

For each species and age class, averages and standard deviations were calculated for slopes 1 and 2, as well as total duration, first quartile duration, maximum frequency, and first quartile frequency. The averages were compared among groups and compared with the data found for American crocodiles in Boucher et al (2020) to check for validity. Individual crocodile vocalizations were also compared within species and age class. Next, the data were standardized using Z-scores and then K-means clustering was performed in RStudio using R [R 4.2.2 GUI 1.79] (R Core Team, 2021). ANOVA analysis was also conducted in RStudio using Welch's correction. The data were analyzed using the Shapiro-Wilk test to determine if it was normally distributed. A Levene's test was conducted to analyze the homogeneity of the variance. If any statistically significant differences were found ($p < 0.05$), the Games-Howell post hoc test was run to determine where the differences are located.

Results

There were 21 crocodiles recorded across 10 surveys. In total, seven individual crocodiles who vocalized were analyzed: two Morelet's juveniles, one Morelet's subadult, two American juveniles, and two American hatchlings.

It appears that the Morelet's subadult group has a lower total duration than the American juvenile group (0.13 s vs 0.21 s). In addition, the Morelet's juvenile Slope 1 is more negative than the American juvenile group. For Slope 2, the Morelet's subadult group is more negative when compared to the American hatchling and juvenile groups. However, it should be noted that this data only includes values from seven individuals (Table 3**).**

Table 3: This table has the average and standard deviation for the measured parameters: total duration (DT), duration of the first quartile ($D_{1/4}$), max frequency (F_{max}), beginning frequency (Beginning), the frequency at the first quartile ($F_{1/4}$), end frequency (F_{end}), the slope of the first quartile (Slope 1), and slope of the remaining three quartiles (Slope 2). S is seconds and Hz is Hertz. It is separated by species and age class. However, each category only has one-two crocodiles in it, with seven vocalizations each.

Measurement	Morelet's Juvenile	Morelet's Subadult	American Hatchling	American Juvenile
DT (s)	0.16±0.05	0.13±0.007	0.16±0.05	0.21±0.03
$D_{1/4}$ (s)	0.04±0.01	0.03±0.001	0.04±0.01	0.05±0.007
F_{max} (Hz)	1031±256	844±133	633±134	666±108
Beginning (Hz)	984±331	797±66	633±134	648±105
$F_{1/4}$ (Hz)	422±199	516±66	360±37	347±107
F_{end} (Hz)	234±66	234±66	219±55	164±48
Slope 1 (Hz/s)	-16373±6929	-10265±2618	-8049±5254	-6229±2155
Slope 2 (Hz/s)	-1838±1698	-2917±159	-1180±242	-1140±447

Visual comparisons of total duration reveal no clear distinction between age class or species, however, there is a lot of individual crocodile difference (Figure 7). All of the Morelet's overlap. There is no overlap between American hatchlings, with some overlap with the Morelet's, but there is overlap between American juveniles.

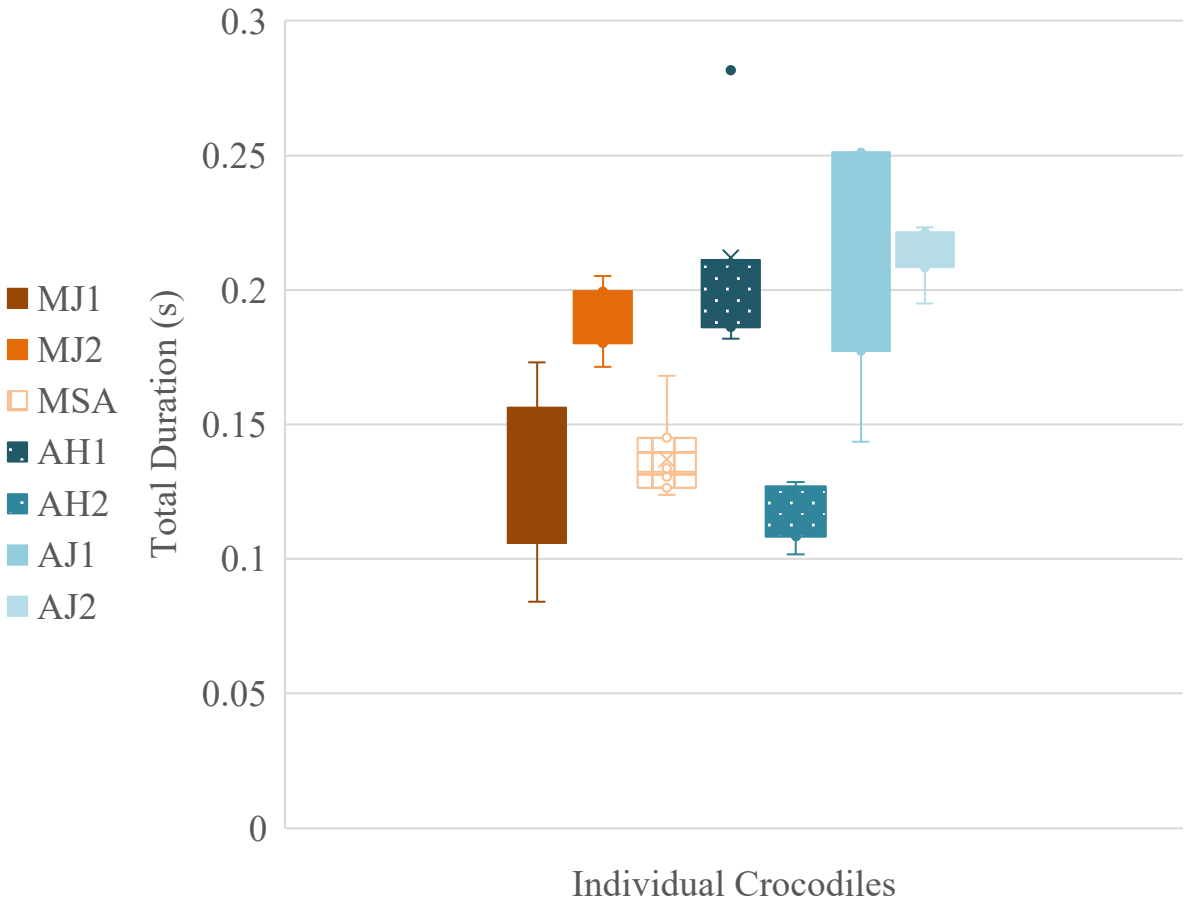


Figure 7: This graph is a box and whiskers plot showing the **total duration** for all seven individual crocodiles. Species are listed as M for Morelet's or A for American. Age class is listed as H for hatchling, J for juvenile, and SA for subadult. Solid colors are for juveniles.

When considering max frequency values for all seven individuals, there is no overlap between American juveniles, but they overlap with other individuals in other species or age classes. This is also true for American hatchlings. All three Morelet's overlap (Figure 8).

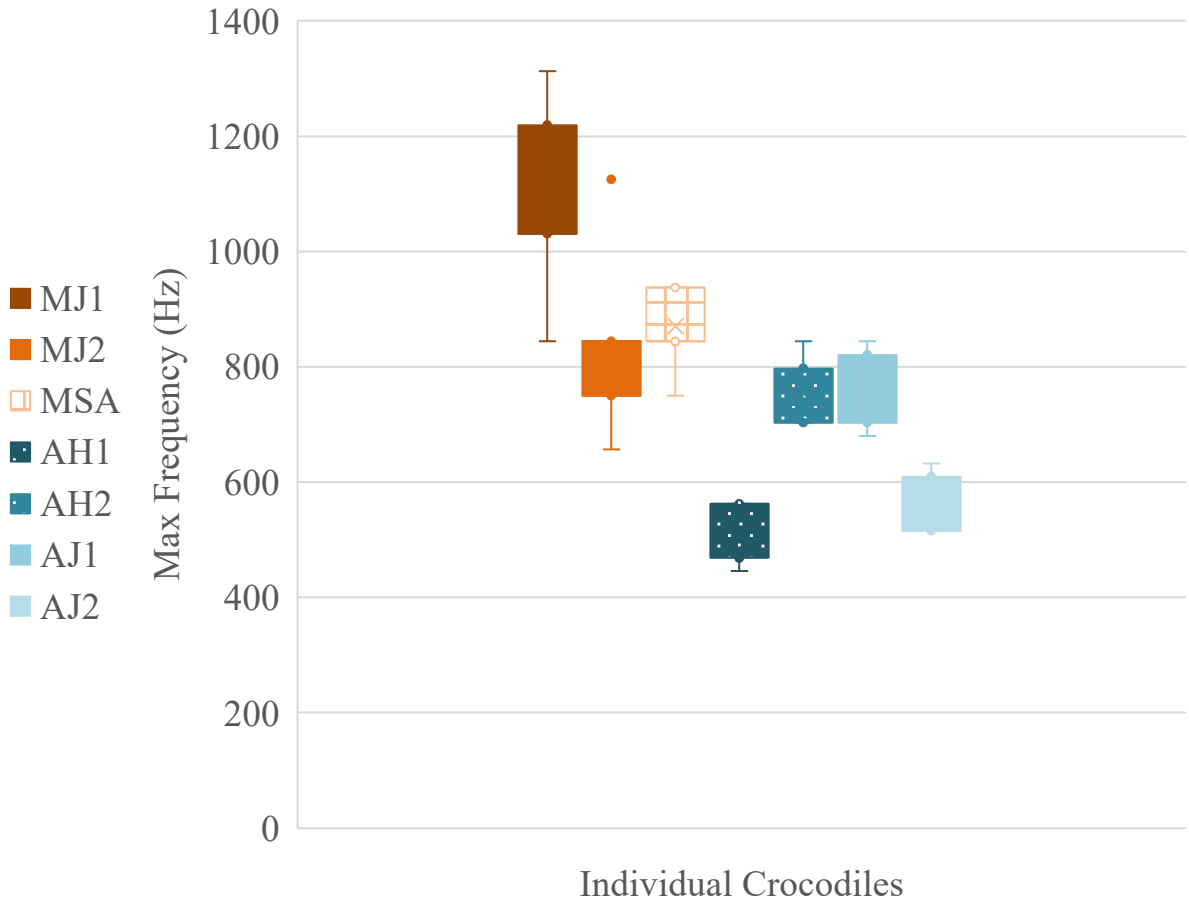


Figure 8: This is a box and whisker plot showing the **max frequencies** for all seven individual crocodiles. Species are listed as M for Morelet's or A for American. Age class is listed as H for hatchling, J for juvenile, and SA for subadult. Solid colors are for juveniles.

There is a slight overlap between American juveniles for beginning frequency, which also overlaps with American hatchlings. The two American hatchlings have no overlap. All three of Morelet's beginning frequency values overlap with each other (Figure 9).

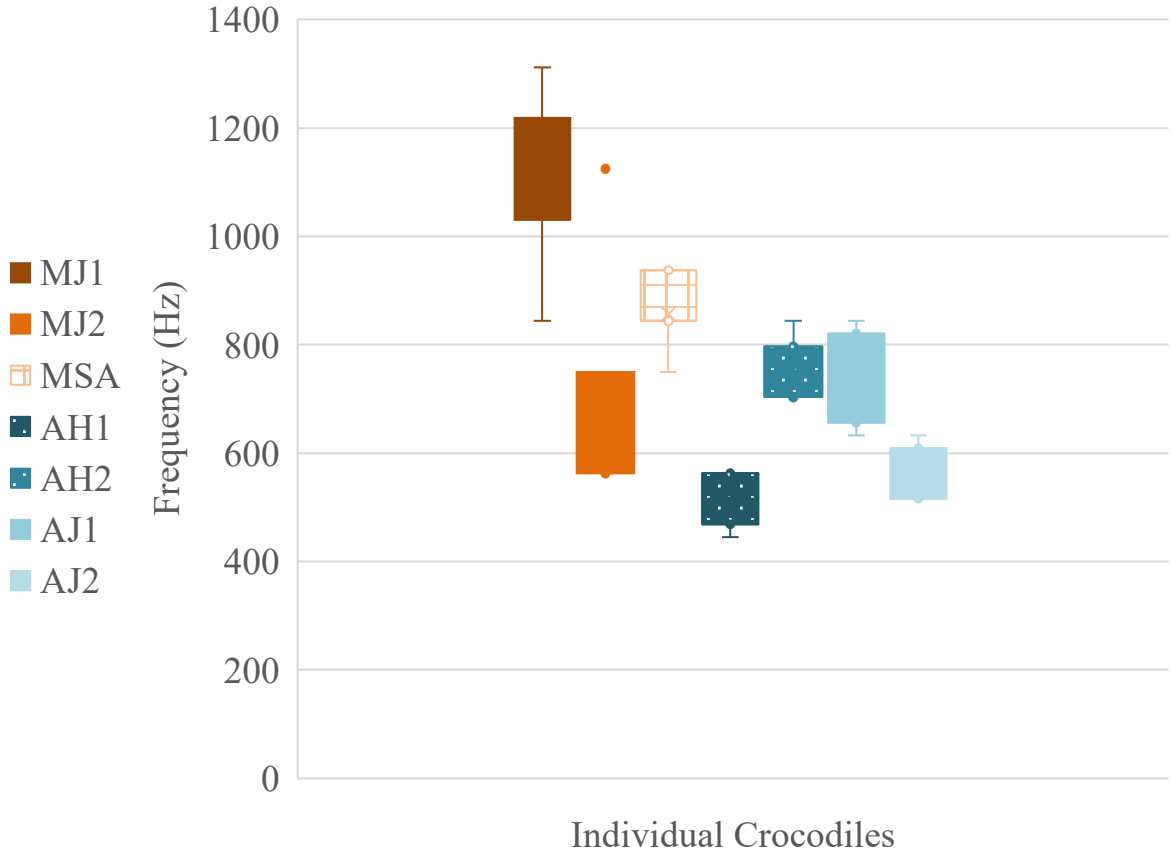


Figure 9: This is a box and whisker plot showing the **beginning frequencies** for all seven individual crocodiles. Species are listed as M for Morelet's or A for American. Age class is listed as H for hatchling, J for juvenile, and SA for subadult. Solid colors are for juveniles.

There is overlap between most individuals for the frequency at the first quartile except between Morelet's Juvenile 1 and American Juvenile 2, and between Morelet's Subadult and American Juvenile 2 (Figure 10).

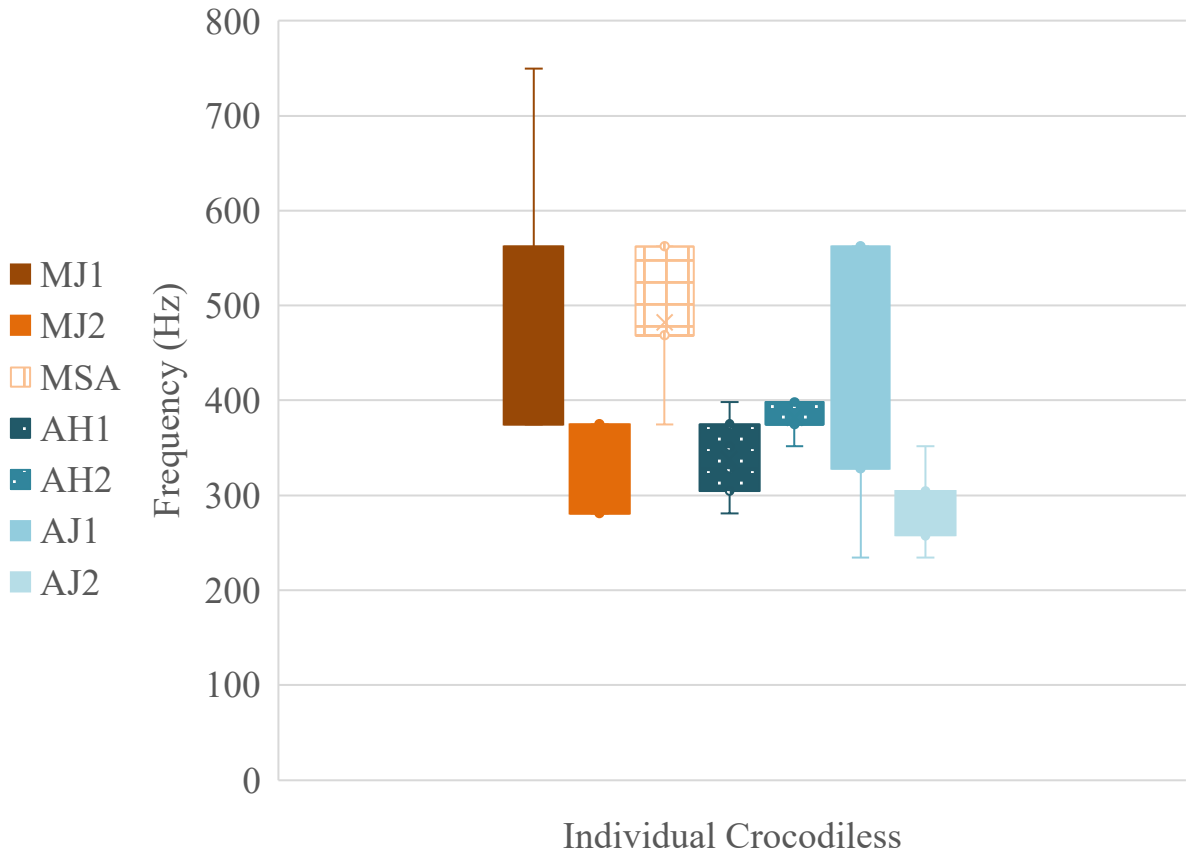


Figure 10: This is a box and whisker plot showing the **frequency at the first quartile** for all seven individual crocodiles. Species are listed as M for Morelet's or A for American. Age class is listed as H for hatchling, J for juvenile, and SA for subadult. Solid colors are for juveniles.

There is overlap for the end frequencies between all of the individuals, except the American hatchlings don't overlap with each other (Figure 11).

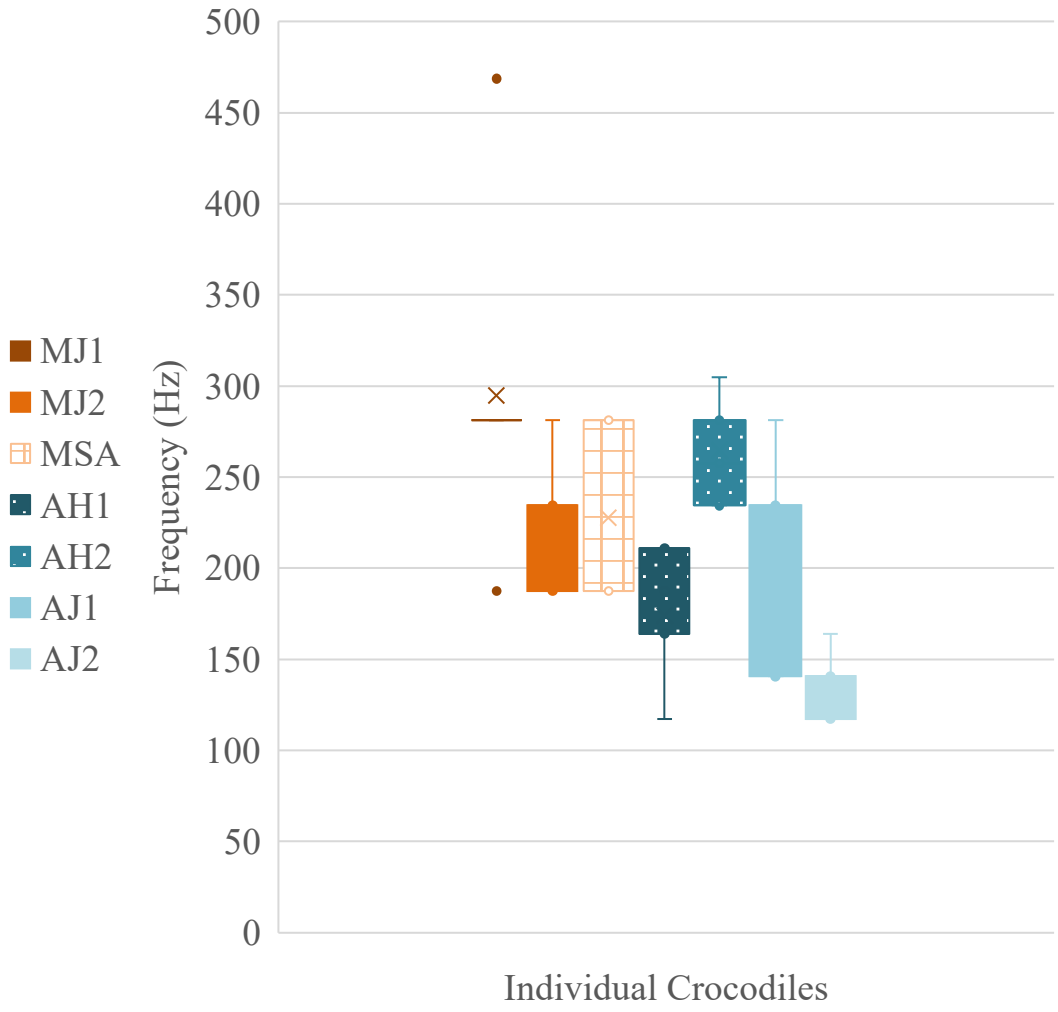


Figure 11: This is a box and whisker plot showing the **end frequencies** for all seven individual crocodiles. Species are listed as M for Morelet's or A for American. Age class is listed as H for hatchling, J for juvenile, and SA for subadult. Solid colors are for juveniles.

In the American hatchling group and American juvenile group, there is no overlap between the two individuals for Slope 1. There is overlap between all of the Morelet's (Figure 12)

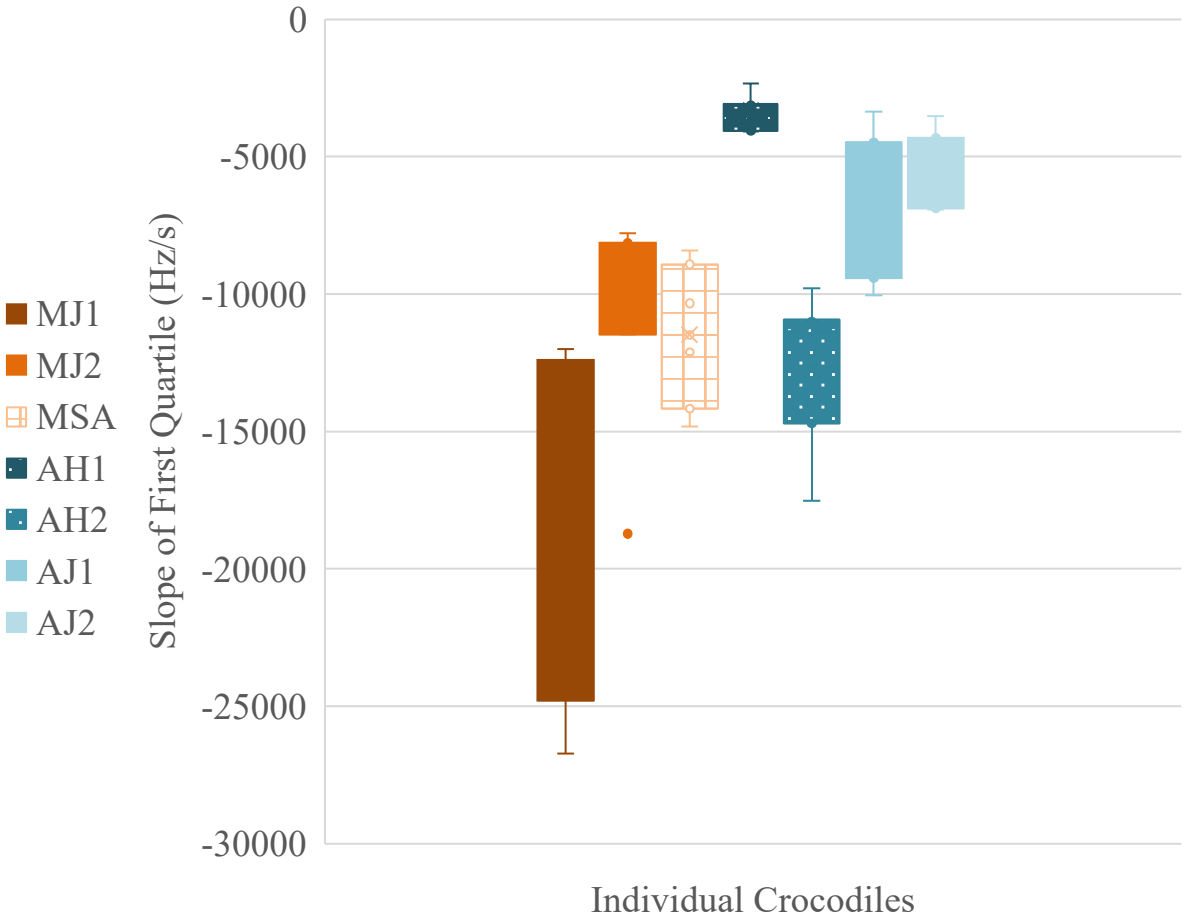


Figure 12: This graph is a box and whiskers plot showing the **Slope 1** for all seven individual crocodiles. Species are listed as M for Morelet's or A for American. Age class is listed as H for hatchling, J for juvenile, and SA for subadult. Solid colors are for juveniles.

There is overlap between all of the individual crocodiles when analyzing Slope 2 (Figure 13).

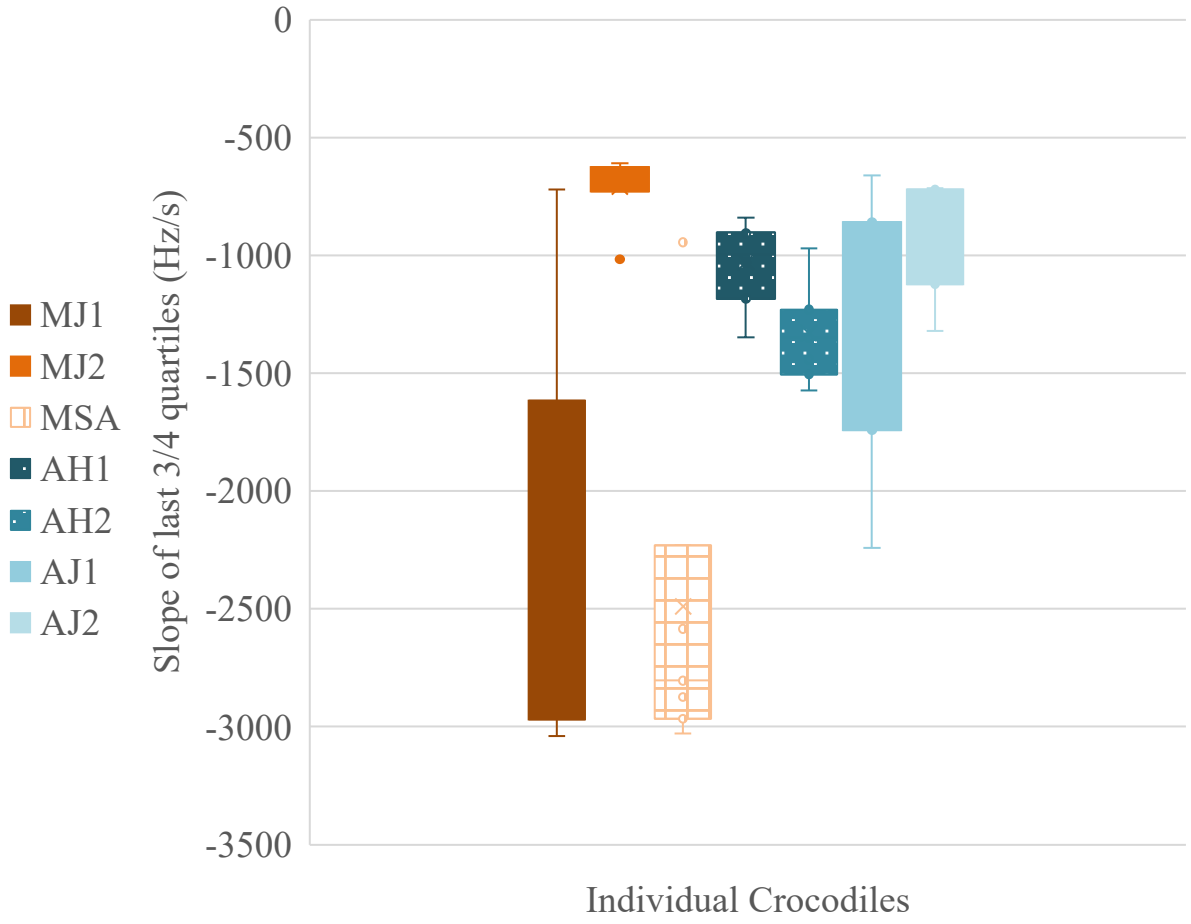


Figure 13: This graph is a box and whiskers plot showing the **Slope 2** for all seven individual crocodiles. Species are listed as M for Morelet's or A for American. Age class is listed as H for hatchling, J for juvenile, and SA for subadult. Solid colors are for juveniles.

For the k-means clustering analysis, the optimal number of clusters was determined to be two, which allowed for all seven points to be grouped into a cluster. Cluster 1 was more widespread, whereas Cluster 2 was more compact (Figure 14). Both clusters contained individuals of both species and contained different age classes. The average size for crocodiles in Cluster 1 was similar to the average size for crocodiles in Cluster 2 (66.27 vs 71.28). There is no clear pattern found in species, age class, or size (Table 4).

Table 4: This table shows the makeup of the different clusters created by RStudio using K-means clustering. Species is listed as Morelet's (M) or American (A). Age class was listed as H for hatchling, J for juvenile, and SA for subadult. The size of the crocodile is listed in centimeters.

Cluster	Species	Age Class	Size (cm)
1	M	J	57.6
1	M	SA	103.5
1	A	H	37.7
2	A	J	77
2	M	J	65
2	A	H	32.4
2	A	J	110.7

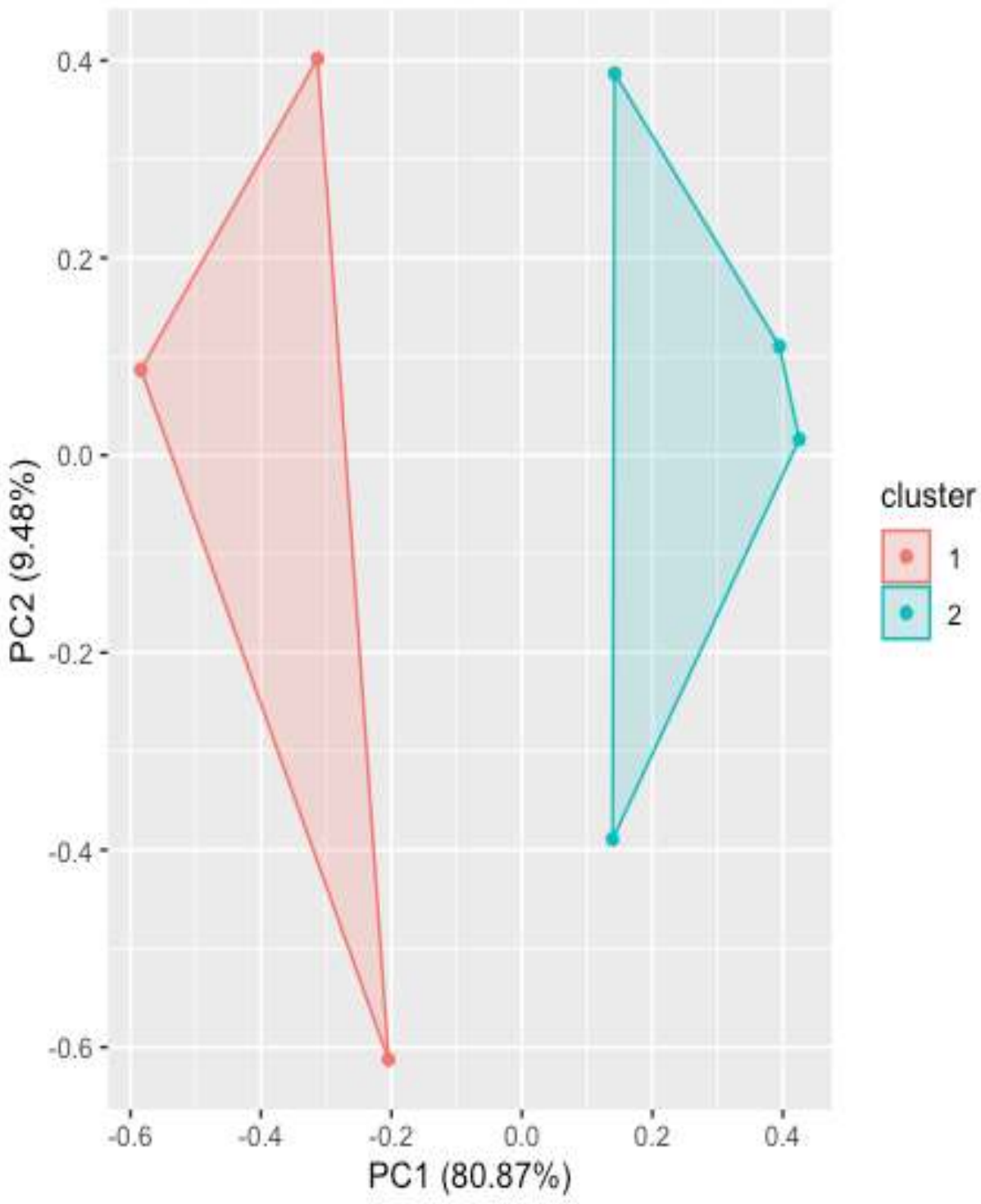


Figure 14: This figure shows the results of the K-means clustering. There are two clusters, labeled 1 and 2. The principal component 1 (PC1) is on the x-axis and the principal component 2 (PC2) is on the y-axis. The percentages are the proportion of how the variance in the data is explained by one of the principal components.

The data were run through an ANOVA test in RStudio, using a Welch's correction. Unlike a classical ANOVA, this correction is to account for the differing variance levels, as the groups did not have the same standard deviations for the majority of the variables. The ANOVA test found a statistical difference between all of the variables, using a confidence interval of 95%. The p-values were statistically significant (<0.05) for every variable tested (Table 5). This test determines if there is at least one statistically significant difference between individual crocodiles.

Table 5: This table has the p-values from the ANOVA test with Welch's correction done on RStudio. The variables tested are beginning frequency (Begin), end frequency (End), total duration, frequency at the first quartile ($F_{1/4}$), the max frequency (Max), slope 1, and slope 2.

Variable	**P-value**
Begin	<0.0000001
End	0.0000004
Total Duration	<0.0000001
$F_{1/4}$	0.000308
Max	<0.0000001
Slope 1	<0.0000001
Slope 2	0.0000099

Although there was a difference found in the variables, the ANOVA test has certain conditions that are expected to be followed, including data are random/independent, the data are normally distributed, and there is homogeneity in the variance. Welch's correction was used to eliminate the issue with unequal variances, however the Shapiro-Wilk test was done to determine whether or not the data were normally distributed. The only variables that had no evidence for non-normality were slope 1 and total duration, meaning that the p-values calculated for the other variables cannot be trusted because the data did not meet the assumptions for the ANOVA test. It is only reasonable to do further testing on those variables that did meet the assumptions, so a Games-Howell Post-Hoc test was done for further interpretation on total duration and slope 1.

A Games-Howell Post-Hoc test is a follow-up test to determine where the statistical differences were found after running the ANOVA test. This test uses multiple comparisons that adjust the p-value to lower the risk of a false positive result. There is a 95% confidence interval, so the difference is statistically significant if the p-value is less than 0.05. When analyzing the post-hoc test for total duration, there are not statistical differences found between Morelet's Juvenile 1 and Morelet's Subadult or American Hatchling 2, between Morelet's Juvenile 2 and American Juvenile 1 or American Hatchling 1, between Morelet's Subadult and American Hatchling 2, between American Hatchling 1 and American Juvenile 2 (Table 6). When analyzing the post-hoc test for slope 1 there are not statistical differences found between Morelet's Juvenile 2 and Morelet's Subadult or American Juvenile 1 or American Hatchling 2, between Morelet's Subadult and American Juvenile 1 or American Hatchling 2, between American Juvenile 1 and American Hatchling 2, and between American Hatchling 1 and American Juvenile 2 (Table 7).

Table 6: This table has the p-values for the Games-Howell Post-Hoc test conducted on **total duration** in RStudio. Species are listed as M for Morelet's or A for American. Age class is listed as H for hatchling, J for juvenile, and SA for subadult. Values in red indicate a statistical difference.

	MJ1	**MJ2**	**MSA**	**AJ1**	**AH1**	**AH2**	**AJ2**
MJ1	-	**0.032**	0.999	**0.034**	**0.011**	0.789	**0.004**
MJ2	-	-	**0.000**	0.858	0.647	**0.000**	**0.019**
MSA	-	-	-	**0.027**	**0.006**	0.166	**0.000**
AJ1	-	-	-	-	0.999	**0.008**	0.999
AH1	-	-	-	-	-	**0.002**	0.999
AH2	-	-	-	-	-	-	**0.000**
AJ2	-	-	-	-	-	-	-

Table 7: This table has the p-values for the Games-Howell Post-Hoc test done on **slope 1** in RStudio. Species are listed as M for Morelet's or A for American. Age class is listed as H for hatchling, J for juvenile, and SA for subadult. Values in red indicate a statistical difference.

	MJ1	**MJ2**	**MSA**	**AJ1**	**AH1**	**AH2**	**AJ2**
MJ1	-	**0.038**	**0.037**	**0.004**	**0.000**	**0.004**	**0.000**
MJ2	-	-	0.993	0.867	**0.009**	0.835	**0.030**
MSA	-	-	-	0.078	**0.000**	0.054	**0.000**
AJ1	-	-	-	-	**0.000**	0.999	**0.001**
AH1	-	-	-	-	-	**0.000**	0.250
AH2	-	-	-	-	-	-	**0.000**
AJ2	-	-	-	-	-	-	-

Discussion

Call structures in the crocodiles analyzed varied between individuals. There was no clear pattern found between size, age class, or species. However, this may have been due to a small sample size. Only one third of the crocodiles recorded were included in analysis because there was a malfunction with the original recording device, which led to recordings being taken on an app on an iPhone, which did not have the same ability to filter out any background noise. It is possible that an expansion of the sample size may reveal patterns between size, age class, or species.

When visually inspecting the spectrograms of all of the individuals, there were some observations that stood out. The slope pattern of the individuals differed, where some had increases within the slope (visually looks like a hill) (Figure 15), others had only negative slopes (Figure 16). Those vocalizations with a portion having a positive slope were found in both species and sometimes occurred multiple times within the same individual.

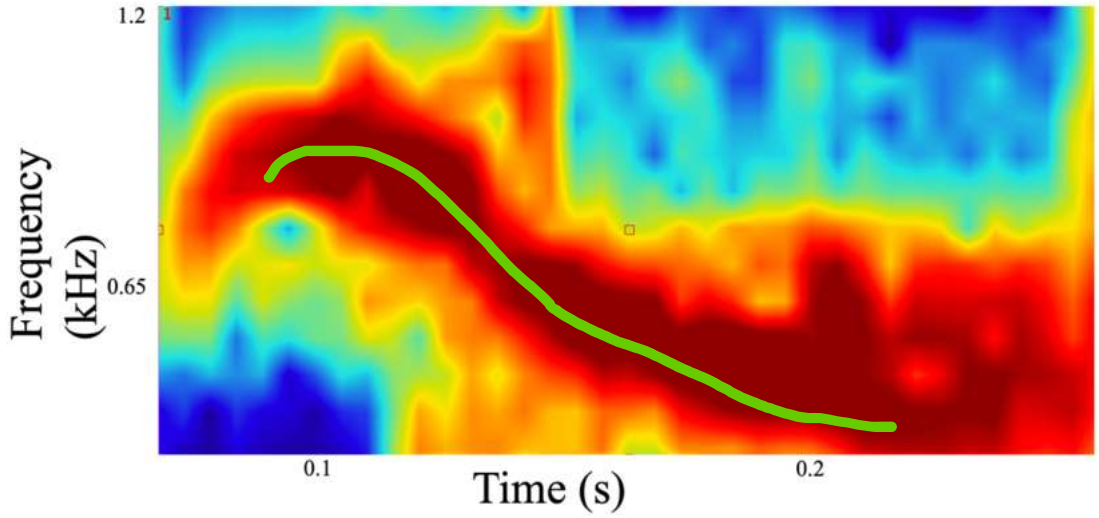


Figure 15: Spectrogram of a vocalization made by a Morelet's juvenile crocodile created in RavenPro. Frequency is on the y-axis, with Hertz (Hz) as the unit, where time is on the x-axis, with seconds (s) as the unit. The green line traces the vocalization's contour.

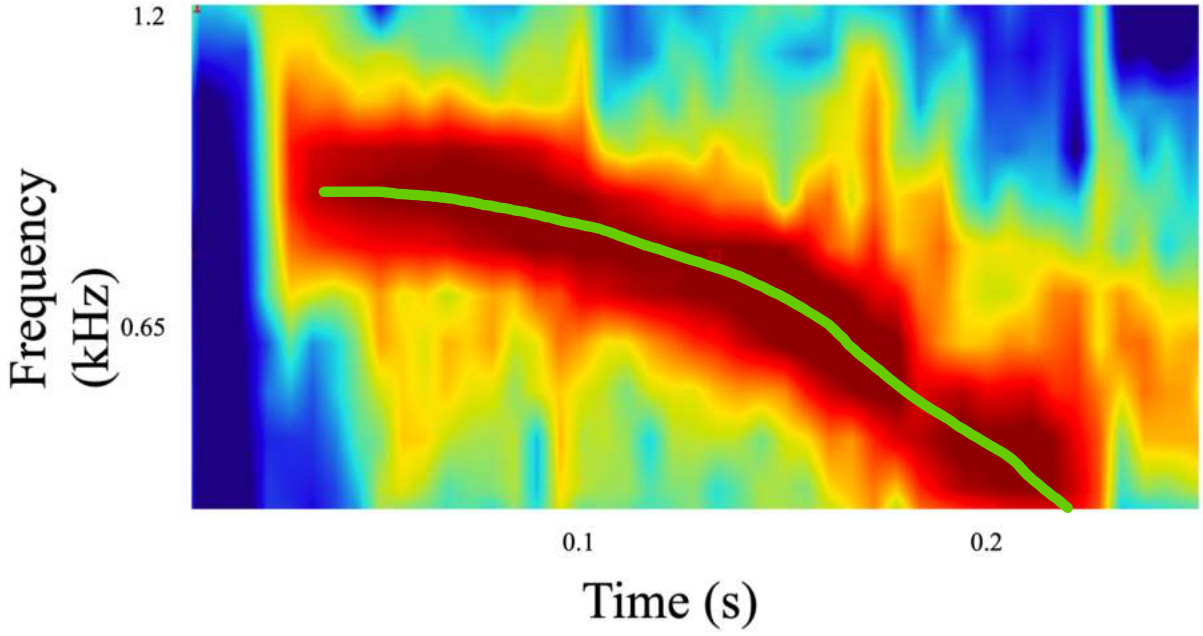


Figure 16: Spectrogram of a vocalization made by an American juvenile crocodile created in RavenPro. Frequency is on the y-axis, with Hertz (Hz) as the unit, where time is on the x-axis, with seconds (s) as the unit. The green line traces the vocalization's contour.

There was also an individual whose call was not similar to any of the other individuals in that it had a long section with an increasing slope before the "standard" downward slope (Figure 17). The embellishment of the vocalization had a majority positive slope, which is different from the standard vocalizations. This sound disqualified this individual from analysis because it was not clear where the "standard" vocalization began. The total duration and slope measurements would have been skewed, so it was deemed an outlier and excluded from analysis.

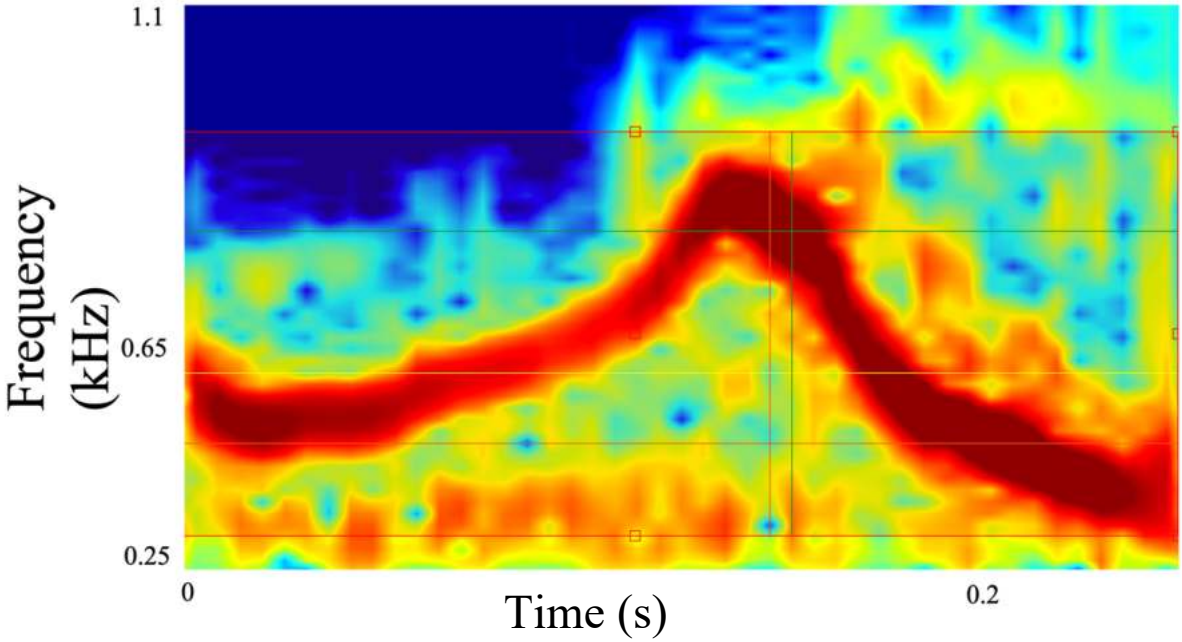


Figure 17: Spectrogram of a vocalization produced by an American juvenile crocodile made in Raven Pro. Frequency is on the y-axis, with Hertz (Hz) as unit, where time is on the x-axis, with seconds (s) as the unit.

After analyzing the data, it is clear that individuals can exhibit very different vocalization structures. There was a lot of variation between individuals within the same age class and species.

For example, the two American hatchlings had no overlap within their values for five out of the seven variables visualized in the box and whiskers plots. In addition to a visual comparison using boxplots, there were statistically different values in the variables analyzed with the Games-Howell pos-hoc test (Tables 6 +7). This suggests that these vocalizations are distinct from one another, although they are of the same species and age class.

It was previously expected that vocalizations made by crocodiles would be stereotypical and have little variation between individuals because they are reptiles, which are generally considered to have simple social and communication systems. However, these data show that there is great variation, between individuals, so these vocalizations are more complex than previously believed. It is possible that these organisms may experience some type of vocal learning or even different regional "dialects", as we see in some birds (Nowicki and Searcy, 2014), although this is just a general speculation. Birds are believed to be closely related to crocodilians (Figure 16), and this may explain why there is variation found in crocodile vocalizations, because there is variation in bird vocalization.

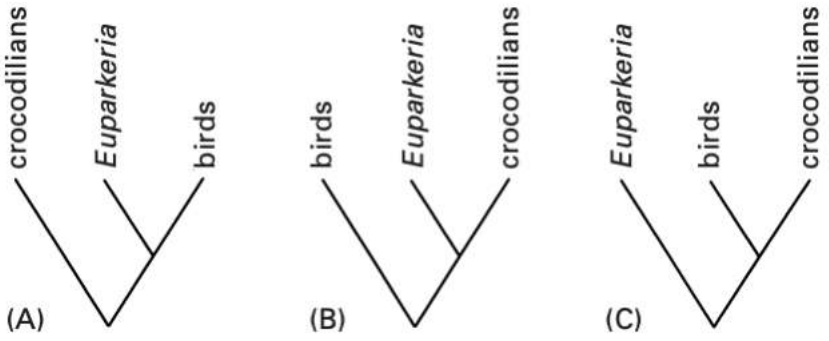


Figure 16: This figure contains three possible phylogenetic trees containing crocodilians, birds, and Euparkeria, taken from Gower and Weber (1998).

There are a lot of benefits to having individually distinct vocalizations, both for research and biological purposes. When it comes to studying them through passive acoustic monitoring, specific individuals, for example a large male, can be tracked easily if their unique call structure is well supported through previous research. This is already in practice, with a variety of taxon being tracked (birds, dolphins, etc.) (Mennill, 2011; Longden et al, 2020). Biologically, a mother crocodile may be able to identify her own offspring's distress calls, which is seen in some birds and mammals (Shapiro, 2010), and can selectively respond to those rather than responding to any hatchling or juvenile distress call. This would increase the fitness of their own offspring.

Distress calls, like those examined in this study, are likely produced for two main reasons: requesting help from a maternal individual or alerting conspecifics of nearby danger (Staton, 1977). In addition, it is possible that there is more than one distress call structure, and they could potentially be used in different situations with varying levels of severity. This is a technique seen in the weeping lizard, who uses simple and complex distress calls to communicate the threat level. In return, conspecific lizards react more to complex calls than simple ones (Ruiz-Monachesi and Labra, 2020). There is also supporting research that mother crocodilians respond more to calls from smaller individuals (Chabert et al, 2015), so it is possible that they would also react to supposed complex calls more frequently and intensely compared to simple calls.

Although this research is limited regarding species, age class, and size, it could still be helpful when implementing PAM for conservation management purposes. It is known that American crocodiles inhabit areas with salt water frequently, and some call types are specific to certain age classes, like mating calls, so PAM could be used for population monitoring.

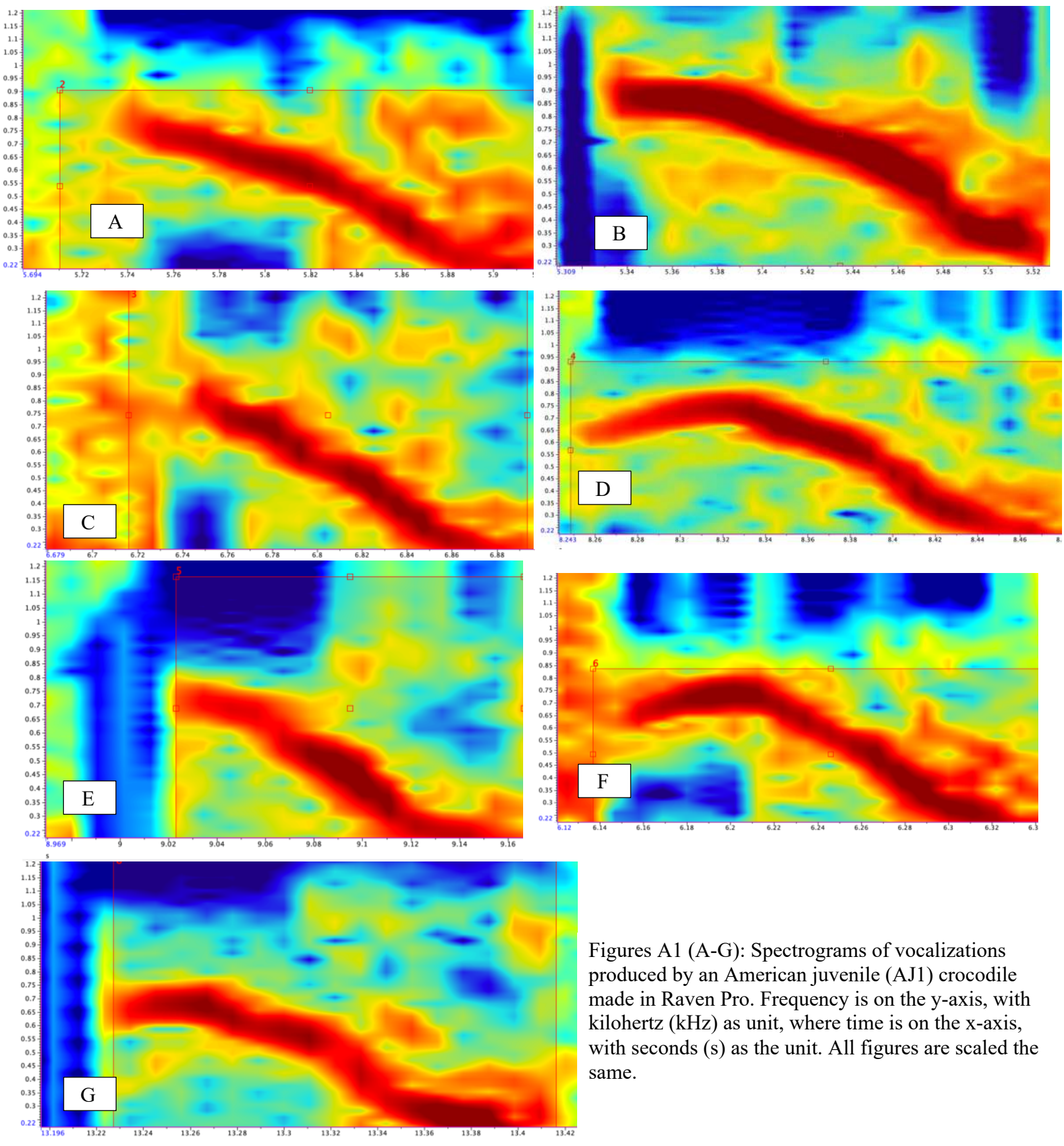
Conclusion

The results of this study show that there are differences in vocalization structures between individual crocodiles. This could help implement passive acoustic monitoring, which can possibly be used to track specific individuals or monitor species abundance as a whole. In the future, this study should be continued over a longer period of time with better recording equipment to ensure that a larger sample size is obtained in order to make robust comparisons between the two species and between age classes. In addition, the calls analyzed during this experiment were specifically distress calls. It would be beneficial for this study to be replicated and incorporate courting calls as well.

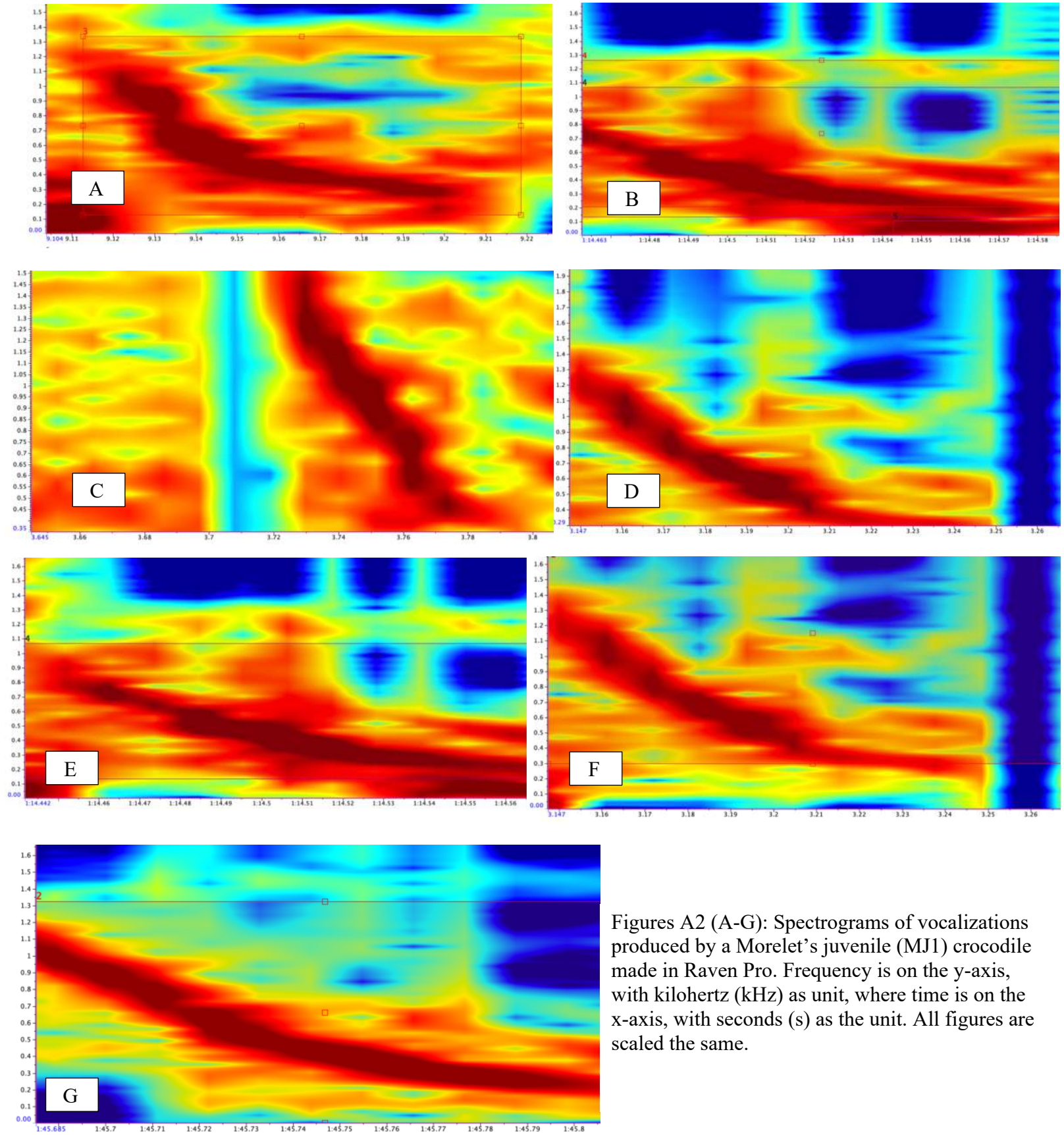
Appendix

Table A1: This table shows the list of all the crocodiles caught during capture surveys conducted in Belize in August 2022. The crocodile ID is the numerical code that the individual was assigned at capture, the location is where the crocodile was caught, the age class is listed as either hatchling, juvenile, subadult, or adult, the species is listed as American (A) or Morelet's (M), and sex is included as male or female. Note that some of the hatchling ID's are the same. This is because a large portion of hatchlings do not make it past their first year, so they are not assigned an individualized code.

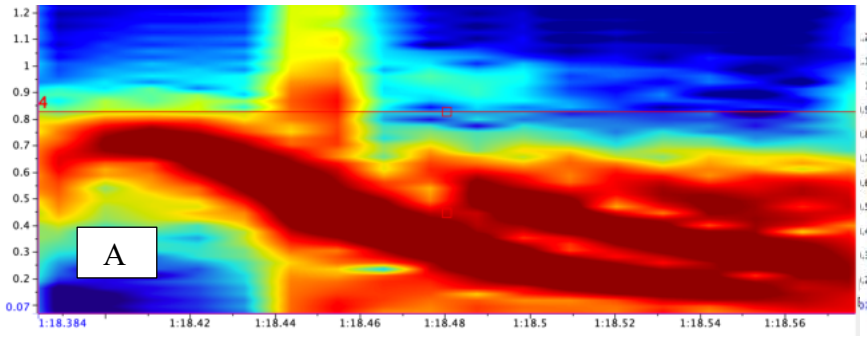
Crocodile ID	Location	Age Class	Species	Sex
990	Monkey River	Adult	A	Female
991	Monkey River	Juvenile	A	Male
992	Monkey River	Juvenile	A	Male
993	Monkey River	Juvenile	A	Male
H10	Cardelli	Hatchling	A	Male
H10	Cardelli	Hatchling	A	Male
994	Cardelli	Juvenile	M	Male
1209	Sittee	Subadult	H	Male
H10	Big Creek	Juvenile	H	Male
H11	Big Creek	Hatchling	A	Male
995	Payne's Creek-Deep River	Juvenile	A	Female
996	Payne's Creek-Deep River	Juvenile	A	Female
1207	Haulover-Burdoun Canal	Juvenile	M	Female
1208	Haulover-Burdoun Canal	Adult	M	Male
H9	Haulover-Burdoun Canal	Juvenile	M	Male
1210	Haulover-Burdoun Canal	Juvenile	M	Male
1211	Haulover-Burdoun Canal	Juvenile	M	Male
1212	Haulover-Burdoun Canal	Juvenile	M	Male
1213	Haulover-Burdoun Canal	Subadult	M	Male
1214	Haulover-Burdoun Canal	Adult	M	Female
1215	Haulover-Burdoun Canal	Juvenile	M	Female

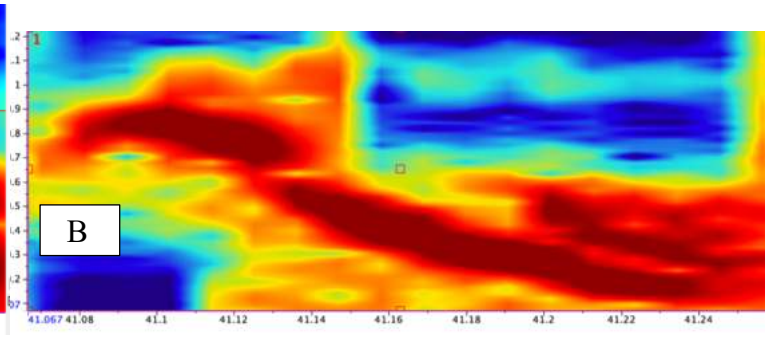


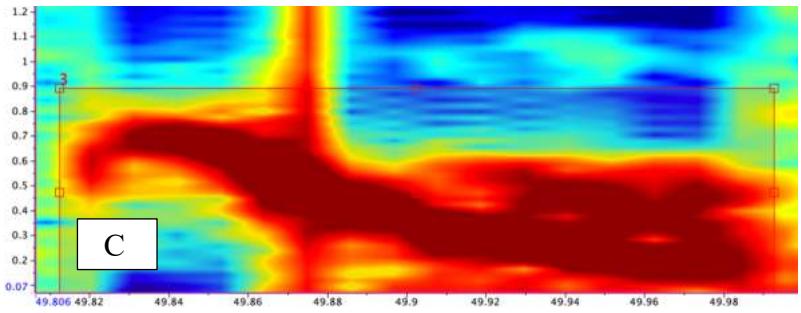
Figures A1 (A-G): Spectrograms of vocalizations produced by an American juvenile (AJ1) crocodile made in Raven Pro. Frequency is on the y-axis, with kilohertz (kHz) as unit, where time is on the x-axis, with seconds (s) as the unit. All figures are scaled the same.

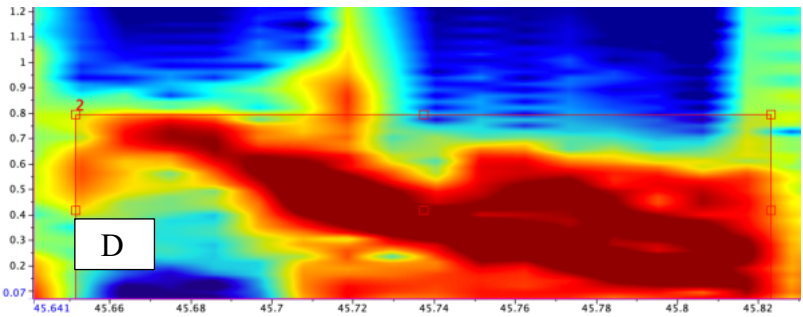


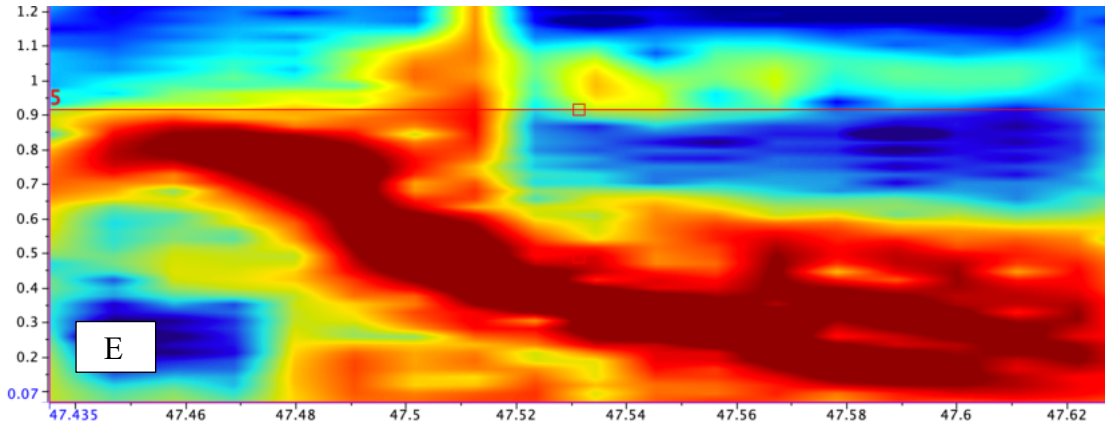
Figures A2 (A-G): Spectrograms of vocalizations produced by a Morelet's juvenile (MJ1) crocodile made in Raven Pro. Frequency is on the y-axis, with kilohertz (kHz) as unit, where time is on the x-axis, with seconds (s) as the unit. All figures are scaled the same.

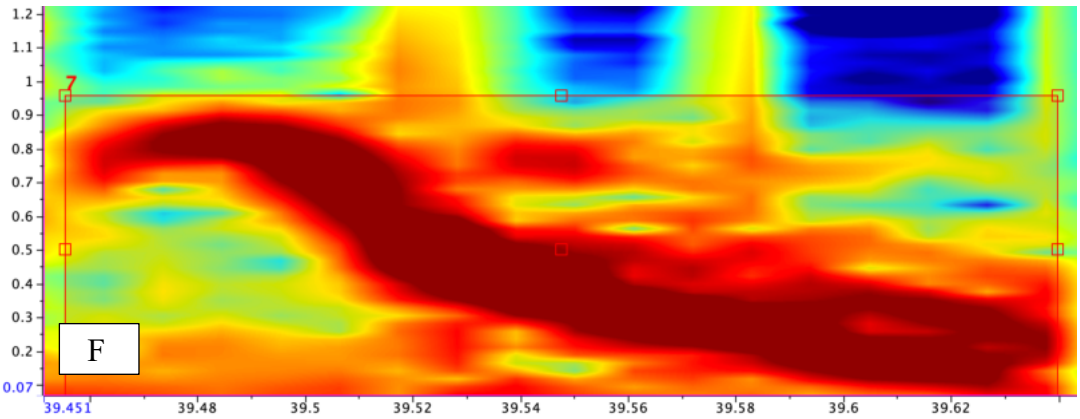


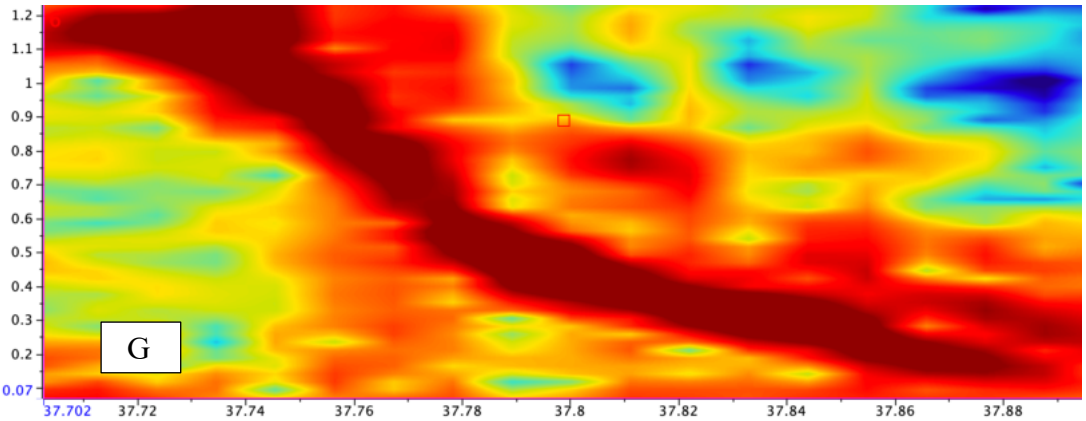




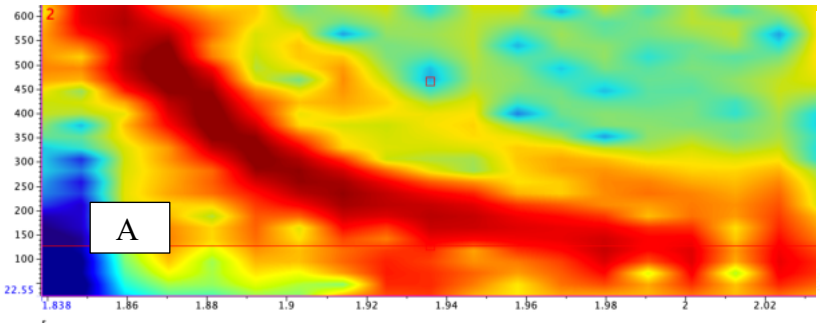


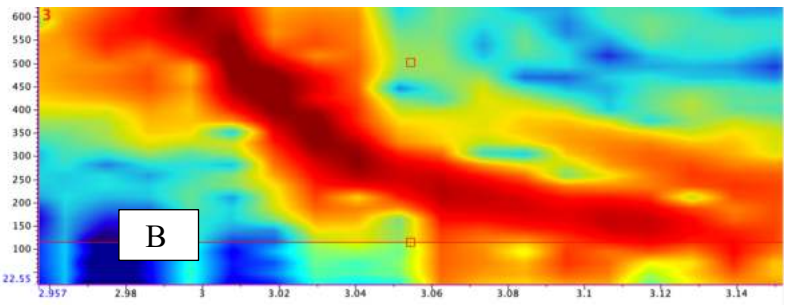


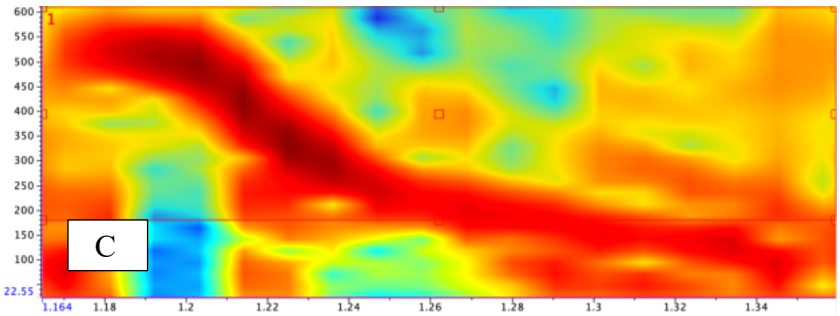


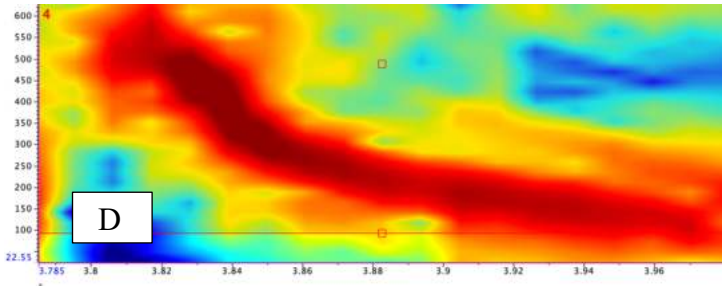


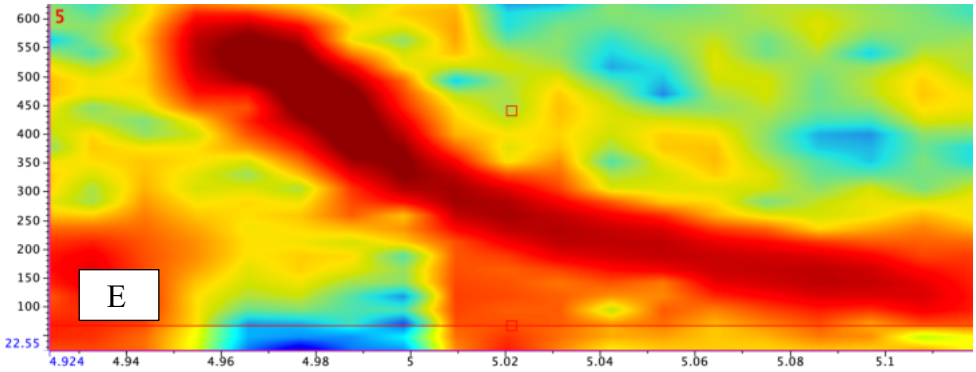
Figures A3 (A-G): Spectrograms of vocalizations produced by a Morelet's juvenile (MJ2) crocodile made in Raven Pro. Frequency is on the y-axis, with kilohertz (kHz) as unit, where time is on the x-axis, with seconds (s) as the unit. All figures are scaled the same.

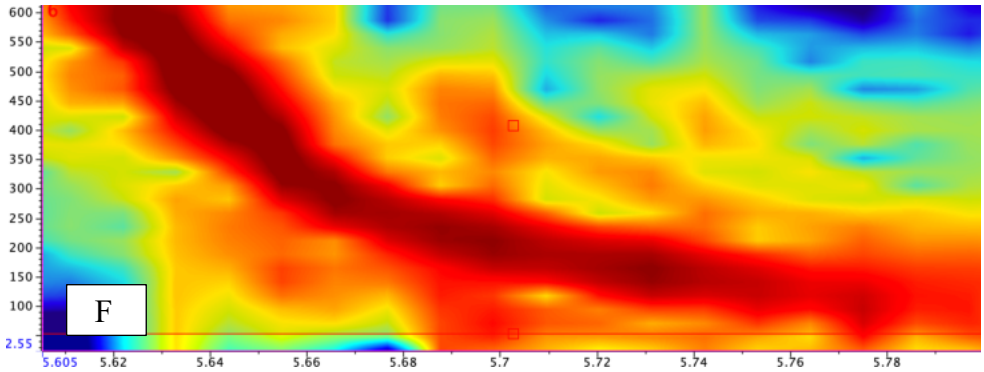


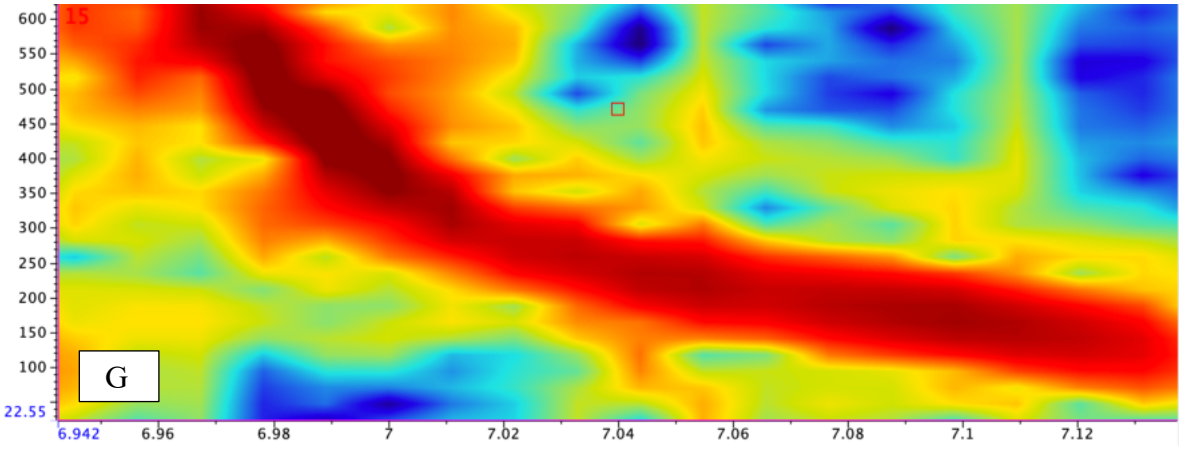




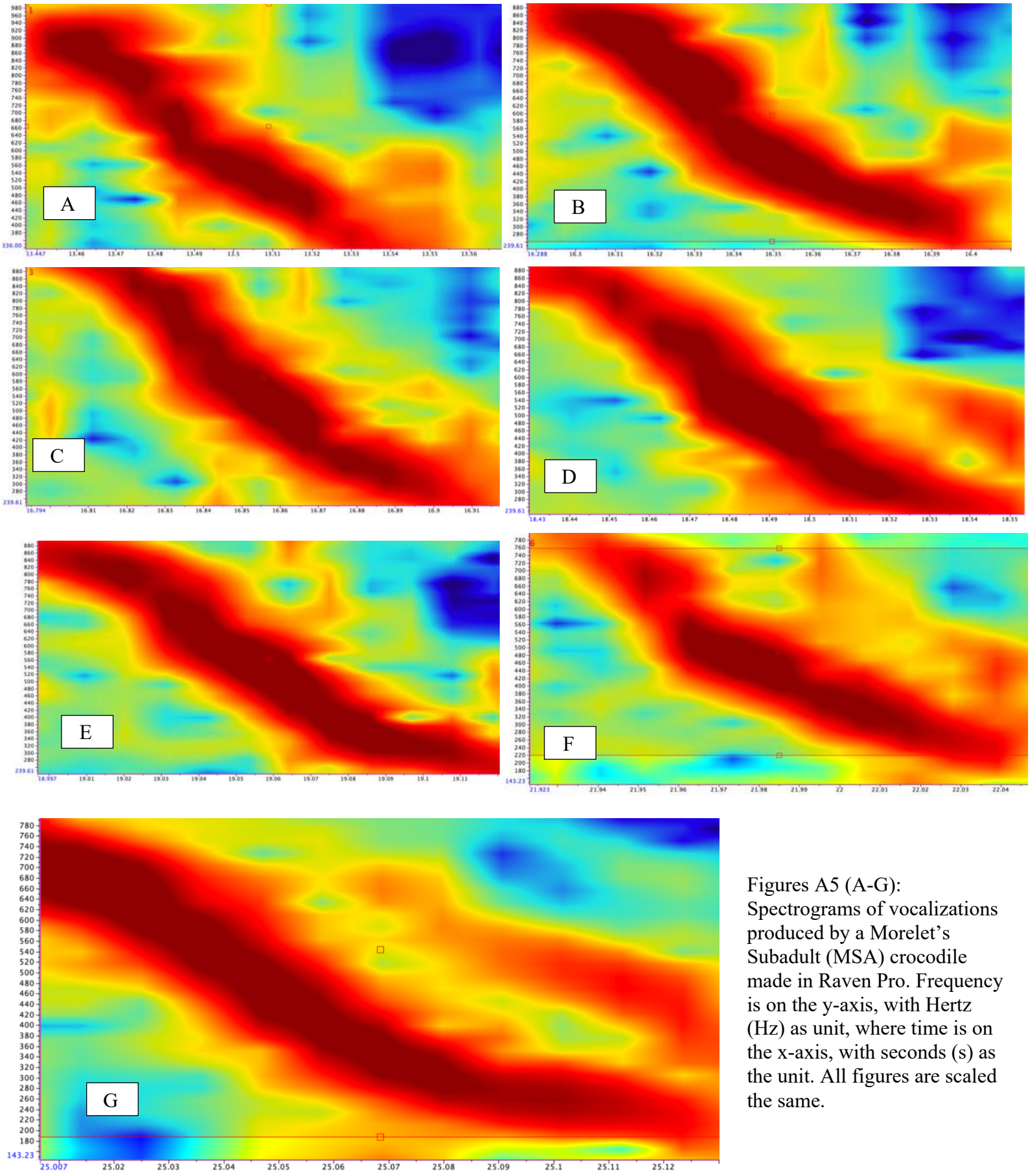




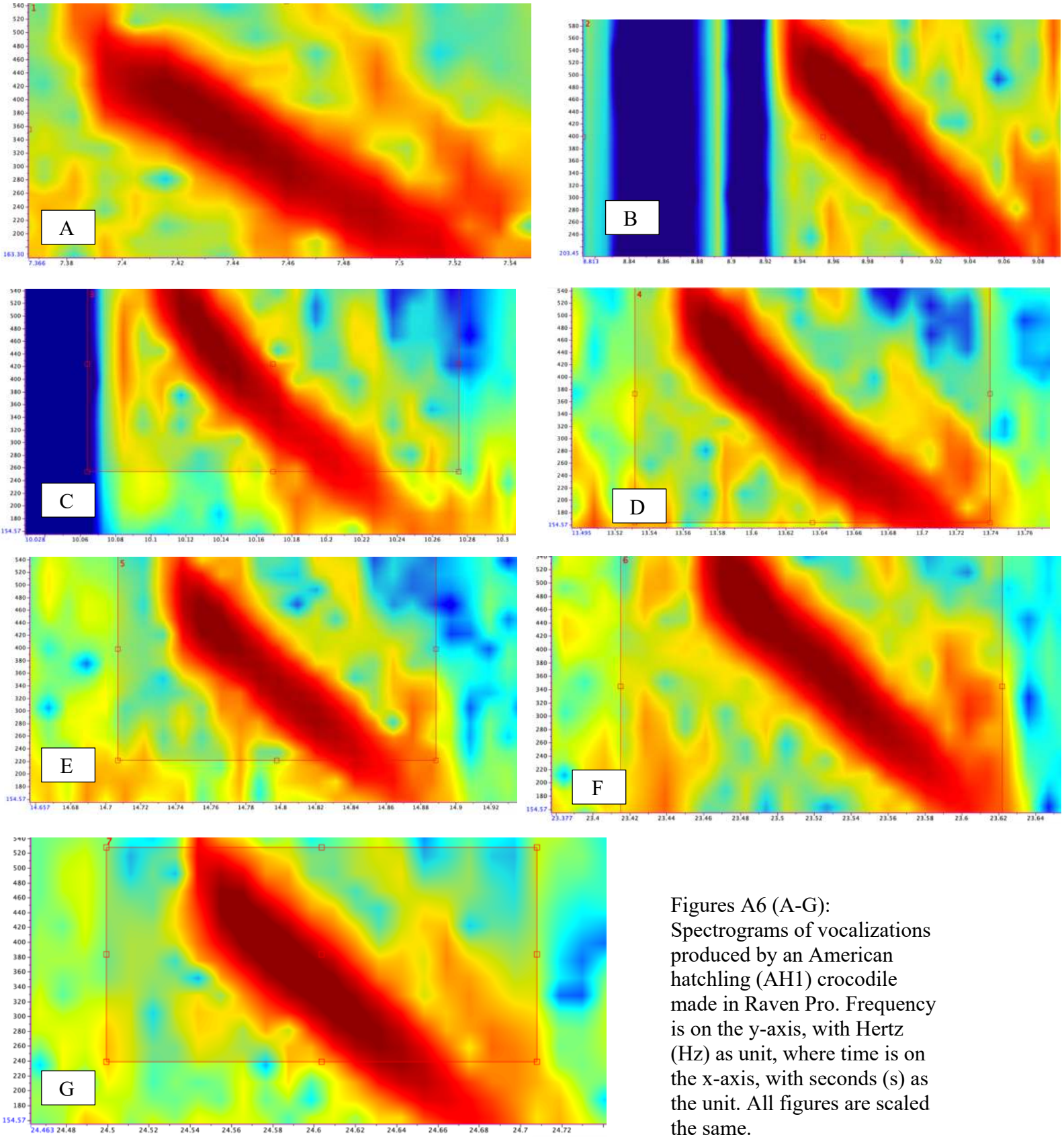




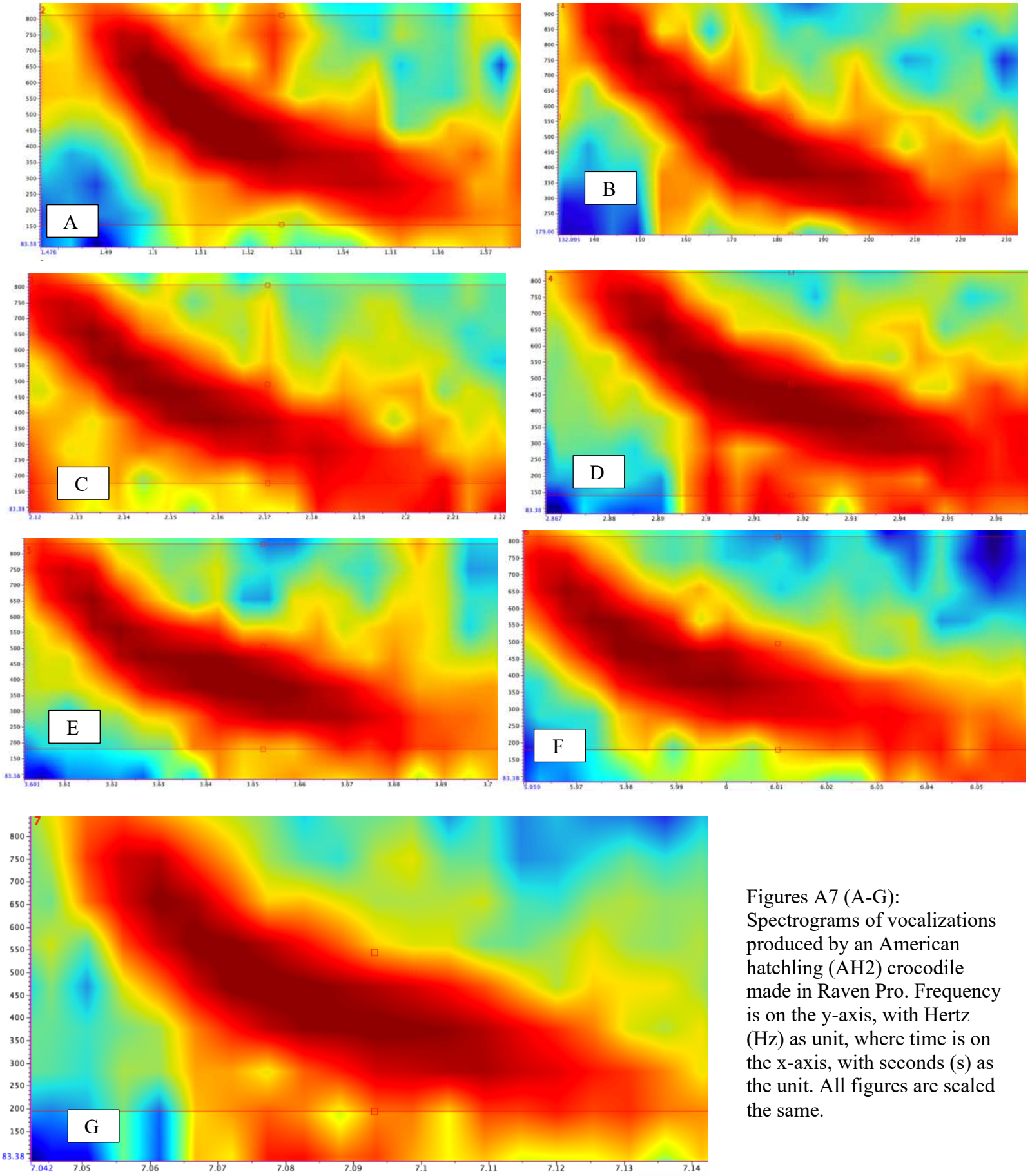
Figures A4 (A-G): Spectrograms of vocalizations produced by an American juvenile (AJ2) crocodile made in Raven Pro. Frequency is on the y-axis, with Hertz (Hz) as unit, where time is on the x-axis, with seconds (s) as the unit. All figures are scaled the same.



Figures A5 (A-G): Spectrograms of vocalizations produced by a Morelet's Subadult (MSA) crocodile made in Raven Pro. Frequency is on the y-axis, with Hertz (Hz) as unit, where time is on the x-axis, with seconds (s) as the unit. All figures are scaled the same.



Figures A6 (A-G): Spectrograms of vocalizations produced by an American hatchling (AH1) crocodile made in Raven Pro. Frequency is on the y-axis, with Hertz (Hz) as unit, where time is on the x-axis, with seconds (s) as the unit. All figures are scaled the same.



Figures A7 (A-G): Spectrograms of vocalizations produced by an American hatchling (AH2) crocodile made in Raven Pro. Frequency is on the y-axis, with Hertz (Hz) as unit, where time is on the x-axis, with seconds (s) as the unit. All figures are scaled the same.

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