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A science scandal that culminated in declaring the Ivory-billed Woodpecker (*Campephilus principalis*) extinct

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The Ivory-billed Woodpecker (*Campephilus principalis*) is an ultra-elusive bird that has repeatedly been feared extinct only to be rediscovered during the past hundred years. An article that was featured on the cover of *Science* in 2005 announced the most recent rediscovery in Arkansas, which was the first report of this species by ornithologists in several decades. Another group of ornithologists reported a series of sightings in Florida the following year, but the issue became controversial when nobody managed to get close enough to an Ivory-billed Woodpecker for a long enough period of time to obtain the clear photo that is regarded as the standard form of evidence for documenting birds. In Louisiana and Florida, video footage was obtained during three encounters with distant birds that were identified in the field as Ivory-billed Woodpeckers. The videos show field marks, body proportions, flights, and other behaviors and characteristics that are consistent with the Ivory-billed Woodpecker but no other species of the region. The five most compelling events in the videos are the focus here, but several additional events are also discussed. During four of the most compelling events, the audio track contains sounds that are consistent with the Ivory-billed Woodpecker. Extensions of previous results include a size comparison and a wingspan estimate that are used to fortify the analysis of two videos from Louisiana. Takeoffs with deep and rapid wingbeats and loud 'wooden' wing sounds, which were overlooked during previous analysis of a video that was obtained in Florida, are consistent with an account by Tanner. Additional events in the Florida video are also discussed, including a sudden maneuver during a swooping flight that coincides with 'spring-like' sounds. This issue started to evolve into a science scandal when critics, who had become entrenched in the position that the Ivory-billed Woodpecker is extinct, used specious arguments to cause a long delay in the publication of the strongest evidence, which should be sufficient to establish persistence. After openly targeting relatively weak evidence, critics avoided engaging in open discourse on the strongest evidence after it was finally published. Some of the leading science journals helped to enable the scandal by failing to provide diligent oversight and publishing biased negative reports on the status of this issue. The scandal culminated in a decision by the U.S. Fish & Wildlife Service to declare the Ivory-billed Woodpecker extinct, which was made in the absence of an open discourse on the strongest evidence and in the wake of an unprecedented spike in published reports of sightings during the searches in Arkansas, Florida, and Louisiana.

Keywords: Ivory-billed Woodpecker; bioacoustics; harmonic oscillator; kent calls; high-pitched alarm calls; double knocks; drumming; avian conservation; avian flight mechanics; flap rate; flight speed

1. Introduction

A good candidate for the most elusive bird in the world would be the Ivory-billed Woodpecker (*Campephilus principalis*),[1–3] which has repeatedly been feared extinct only to be

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rediscovered during the past hundred years. Other species have been rediscovered, but the Ivory-billed Woodpecker is a species of great interest in a region that is easily accessible to a large number of bird watchers. Nobody has ever obtained a clear photo of this species without knowing the location of an active nest. When the location of a nest was known, clear photos were obtained at the nest but not away from the nest. During the past several decades, there have been many reports of sightings, but nobody has obtained a clear photo. Ornithologists did not manage to obtain a clear photo during multi-year searches at sites in Arkansas[4] and Florida[5] at which they were convinced these birds were present. Prior to those efforts, the Ivory-billed Woodpecker had not been reported by ornithologists in several decades. This remarkable history of elusiveness has been attributed to an outlying combination of factors (not just rarity) related to habitat (vast and remote swamp forests where visibility is limited to short distances) and behavior (wide ranging and extremely wary birds that lack conspicuous behaviors).[6]

Despite dozens of sightings during the searches in Arkansas and Florida, the persistence of the Ivory-billed Woodpecker became controversial when nobody managed to obtain the clear photo that is regarded as the standard form of evidence for documenting birds. There is no logical basis for requiring a particular type of evidence. It should be possible to resolve this issue with other types of evidence, such as video footage that shows characteristics consistent with the Ivory-billed Woodpecker but no other species and for those characteristics to be sufficient in number to rule out the plausibility of any alternative explanation. Video footage that meets these criteria was obtained during three encounters with birds that were identified in the field as Ivory-billed Woodpeckers.[6–11] In recent decades, nobody has gotten close enough to an Ivory-billed Woodpecker for a long enough period of time to aim and focus a camera and obtain a clear photo, but the videos show distant birds with field marks, body proportions, flights, and other behaviors and characteristics that are consistent with that species but no other species of the region. Nobody has proposed plausible alternative explanations for any of the events that appear in the videos or challenged this evidence, which is the strongest that has been obtained during the past several decades. The controversy started to evolve into a science scandal when specious arguments were used to prevent the strongest evidence from being published and included in a debate on the persistence of the Ivory-billed Woodpecker.[11]

The five most compelling events in the videos are the focus here, but several additional events are also discussed. During four of the most compelling events, the audio track contains sounds that are consistent with the Ivory-billed Woodpecker. During one of the other events, there are 'spring-like' sounds that coincide with a sudden flight maneuver. In order to lay out complete arguments, all of the details of the most compelling events are discussed here, including some analysis that was published previously. Additional results presented here include estimates of body size and wingspan that are used to fortify the analysis of two videos that were obtained in Louisiana. It was previously noted[6,7] that a perched woodpecker in one of the Louisiana videos is a large woodpecker that has several behaviors and characteristics consistent with the Ivory-billed Woodpecker but not the Pileated Woodpecker (*Dryocopus pileatus*), which is the only other large woodpecker that has ever been documented north

of the Rio Grande in North America. It is demonstrated here that the woodpecker in that video is comparable in size to an Ivory-billed Woodpecker specimen that is near the maximum size for that species; it is therefore larger than any Pileated Woodpecker. The combination of the wingspan and a diagnostic flap style (the wings are folded closed in the middle of each upstroke) are used to conclude that the bird in the other Louisiana video is a large woodpecker. An expert on woodpecker flight mechanics previously came to the same conclusion on the basis of an analysis (that does not require the wingspan) of the horizontal and vertical motions of the wingtips through a flap cycle.[7] After reaching the conclusion that the bird in the video is a large woodpecker, the main conclusion follows from the flap rate, which is about ten standard deviations greater than the mean flap rate of the Pileated Woodpecker.[7] The field marks, wing shape, flight speed, and swept-back appearance of the wings are consistent with that species but not the Pileated Woodpecker.[6,7] Also presented here is a distinguishing characteristic that was overlooked during previous analysis of a video that was obtained during an encounter with two Ivory-billed Woodpeckers in Florida. A 'wooden' wing sound is audible during takeoffs by both of the birds, which occur within a few seconds of each other. The combination of deep and rapid wingbeats and wing sounds that are loud enough to be audible from a distance is consistent with the Ivory-billed Woodpecker but no other species of the region. Earlier in the same event, the combination of the field marks and a remarkable upward swooping landing with a long vertical ascent is also unique to the Ivory-billed Woodpecker.[6] Some of the supplementary videos discussed here were previously published in an open access article,[6] but all of the supplementary material is available at a repository.[12] The datasets analyzed here are also available at a repository.[13]

The videos provide more than just evidence. They show various flights and other behaviors that do not appear in the only existing historical film, which was obtained during a study at the last known nests in 1935. When the Ivory-billed Woodpecker was thought to be extinct, it seemed that historical accounts (some of which are frustratingly lacking in details) were the only existing source of information on many of the behaviors of this fascinating species. Accounts of a flight that is "graceful in the extreme" by Audubon[14] and a landing with "one magnificent upward swoop" by Eckleberry[15] suggest that the Ivory-billed Woodpecker has extraordinary flights; gliding flights were described by Audubon[14] and Christy;[16] Tanner[2] left accounts of short flights between limbs, deep and rapid flaps during takeoffs, noisy wingbeats, and rapid wingbeats in cruising flight; but no flights appear in the historical film. Several calls of the Ivory-billed Woodpecker are described in the literature, but only the 'kent' calls were captured in the historical recording. The Ivory-billed Woodpecker and other *Campephilus* woodpeckers signal with double knocks (some have a descending series of knocks) rather than the drumming that is typical of most woodpeckers, but no double knocks are visible or audible in the historical film. The rediscovery of the Ivory-billed Woodpecker opened up an opportunity for anyone fortunate enough to obtain video footage of these birds to make new discoveries about them.

2. The Making of a Science Scandal

It took less than a year for controversy to arise after the announcement of the rediscovery of the Ivory-billed Woodpecker. In the years that followed, critics became entrenched in the position that the Ivory-billed Woodpecker is extinct, and the issue evolved into a science scandal that needs to be recognized for what it is in the interest of conservation. The threshold at which an issue becomes a science scandal is subjective, but this issue has the following qualifications: (1) it rose to a high level of interest in the science community; (2) there is something important at stake; and (3) the truth has been obscured as a result of ignorance, negligence, and shenanigans. The persistence of the Ivory-billed Woodpecker has been prominently covered by the leading science journals; for example, after appearing on the cover of *Science* in 2005, this issue was singled out by that journal as one of the "Areas to Watch in 2006." The conservation of an iconic species is at stake, but the establishment of a conservation program has been delayed by folly and politics. There had already been decades of folly and politics prior to the most recent rediscovery, but these problems escalated in the years that followed.[11]

The first step in crossing the line from controversy to scandal was the use of specious arguments to stifle open discourse by delaying the publication of the strongest evidence for a decade.[11] A by-product of the more than forty submissions that it took to get the strongest evidence published is a collection of comments by anonymous reviewers (specific examples are discussed in Ref. 11) that reveal a lack of awareness of basic facts and, in some cases, seem to suggest intentions other than seeking the truth. Open discourse is an essential process for bringing out the truth in science, but open discourse on this issue has been selective. Critics were outspoken in dismissing relatively weak evidence that was obtained in Arkansas, but they have avoided open discourse on the strongest evidence. After the strongest evidence was finally published, nobody came forward to openly repeat any of the specious arguments that were used to delay its publication. The combination of openly targeting relatively weak evidence, opposing the strongest evidence behind the scenes, and avoiding open discourse on the strongest evidence seems to suggest intentions other than seeking the truth.

After a topic is covered in the leading science journals, it is often appropriate to report further developments in the same journals. In this case, however, some of the leading science journals actually helped to enable the scandal.[11] After the first video was obtained, the editors of *Science* and *Nature* were informed of new evidence that is stronger than the evidence that was presented in the original paper, but they dismissed the only new evidence that anyone had managed to obtain without giving it any consideration. Those journals subsequently published reports on the status of this issue[17,18] that provided high-profile platforms for critics to air unsupported opinions, falsely stated that no new evidence had been obtained, and sullied the issue by mentioning that a non-scientist had faked a photo; there was no mention of the strongest evidence in those reports. Another way in which science journals have helped to enable the scandal is by failing to provide diligent oversight that has been lacking for this issue.[11] For example, a submission to the *Proceedings of the*

National Academy of Sciences was rejected on the basis of an unfounded suggestion that the speed of one of the videos had been altered in order to increase the apparent flap rate and flight speed by a factor of two. Resorting to a suggestion of fraud was a clear indication that the evidence cannot be refuted with logical arguments, but there was no attempt to confirm that the video is genuine.

The scandal culminated in the announcement of a decision by the U.S. Fish & Wildlife Service to declare the Ivory-billed Woodpecker extinct,[19] which was made in the absence of an open discourse on the strongest evidence and in the wake of published reports of dozens of sightings during the searches in Arkansas, Florida, and Louisiana. Coming the day after the publication of Ref. 11, this announcement motivated additional analysis of the videos that is discussed in the sections that follow.

3. A Woodpecker that is Larger than any Pileated Woodpecker

Following the announcement of the rediscovery of the Ivory-billed Woodpecker in Arkansas, there were efforts to find these birds in several other states. I decided to conduct a search in the Pearl River swamp in Louisiana, where there had been recent reports of sightings. I used approaches that had been pioneered during the search in Arkansas, such as drifting quietly through appropriate habitat in a kayak in order to get as close as possible to these extremely wary birds before being detected. I also spent some time keeping watch from tall trees that provide clear views out over the treetops. This approach was motivated by the fact that Ivory-billed Woodpeckers are known from historical accounts to fly over the forest to distant foraging sites. In order to have a reasonable chance of finding these birds, it is necessary to spend long periods of time in the field. One of the factors that favored the success of my search was an opportunity to spend long periods of time stationed at the Stennis Space Center, which is located on the Mississippi side of the Pearl River swamp. I began the search in the fall of 2005 and had nine sightings along English Bayou during the next two and a half years. One of the videos was obtained during a visit to the Choctawhatchee River swamp in Florida, where there had been recent sightings.[5]

In a concentrated area along English Bayou during a five-day period in February 2006, I had five sightings and twice heard the kent calls of the Ivory-billed Woodpecker. On February 16, I had an excellent view from close range of the white trailing edges and black leading edges on the dorsal surfaces of the wings of an Ivory-billed Woodpecker that flushed and quickly flew into cover (with deep and rapid wingbeats consistent with an account by Tanner). On February 17, an Ivory-billed Woodpecker glided low across the bayou on fixed wings (in a flight consistent with an account by Audubon) and provided an excellent view across the dorsal surfaces of the wings. On February 18, I heard kent calls coming from behind a fallen tree on the bank. While I waited for an opportunity to obtain a photo as illustrated in Fig. 1, kent calls started coming from another bird on the opposite side of the bayou behind me. After the second bird apparently saw me near the first bird, there were a few harsh scolding calls from that direction and then a series of high-pitched calls. At the same location on February 20, I came upon an Ivory-billed Woodpecker that was perched

Fig. 1. Artistic recreation by Michael DiGiorgio of an encounter with two Ivory-billed Woodpeckers in the Pearl River swamp.[6] Kent calls from one of the birds was coming from behind a fallen tree as I waited for it to move into view. An American Robin (*Turdus migratorius*) was scolding from above. Moments later, kent calls started coming from behind me on the opposite side of the bayou.

before flushing into the woods. The same high-pitched calls then began coming from that direction. After ten minutes of tracking the movements of the high-pitched calls, I detected motion deep in the woods at a distance that was later determined to be 128 m from my observation position. I never managed to find the bird within the clutter of vegetation, but I managed to capture video footage of a large woodpecker that was perched, took two flights, and engaged in other behaviors.

A size comparison became possible after the perch tree blew down and part of it was collected in 2008. The tree specimen was cut to include forks that facilitated scaling. It can be difficult to recognize a tree when there is even a small change in the viewing angle, but it is clear from the photos in Fig. 2 that the tree specimen was cut from the perch tree. The Ivory-billed Woodpecker is one of the largest woodpeckers in the world. Size parameters that may be appropriate for comparison in images include length (from tip of bill to tip of tail) and body size (cross-sectional dimensions). The length of the Ivory-billed Woodpecker ranges up to 51 cm, with averages of 45.4 cm for fifteen adult males and 47.1 cm for eleven adult females.[2] There do not appear to be any published data on body size, but ranges have been published for body mass and the dimensions of openings to nest cavities,

Fig. 2. Comparison of the tree specimen with an image from the 2006 video and photos that were obtained shortly after the video was obtained. The photo in the center was scaled horizontally and vertically by slightly different amounts to compensate for the fact that it was obtained from a closer vantage point at an angle looking slightly upward. The dashed lines indicate forks and other features that line up.

which are closely related to body size (excessively large cavity entrances allow easier access to predators). The smallest Ivory-billed Woodpeckers are more massive than the largest Pileated Woodpeckers;[20,21] the smallest openings to Ivory-billed Woodpecker cavities are larger than the largest openings to Pileated Woodpecker cavities;[5] the fact that the ranges for these quantities are disjoint for the two large woodpeckers suggests that the ranges for body size are also disjoint for these species.

For a previous size comparison,[6] I borrowed a Pileated Woodpecker specimen but was unable to borrow an Ivory-billed Woodpecker specimen (there is no way to replace specimens of that species if lost or damaged). In the improved size comparison in Fig. 3, the woodpecker in the 2006 video is compared with images of specimens of both of the large woodpeckers, which were scaled using the tree specimen and measuring sticks that appear at higher resolution in Fig. S1. Two forks in the tree were used to scale frames from the video relative to a photo of a Pileated Woodpecker specimen that was mounted on the tree specimen along with a meter stick. A large baseline favors accurate scaling, and the forks are separated by 1.41 m. The photos of eight male and eight female Ivory-billed Woodpecker specimens appearing in Fig. S2 were obtained at the Smithsonian National Museum of Natural History.

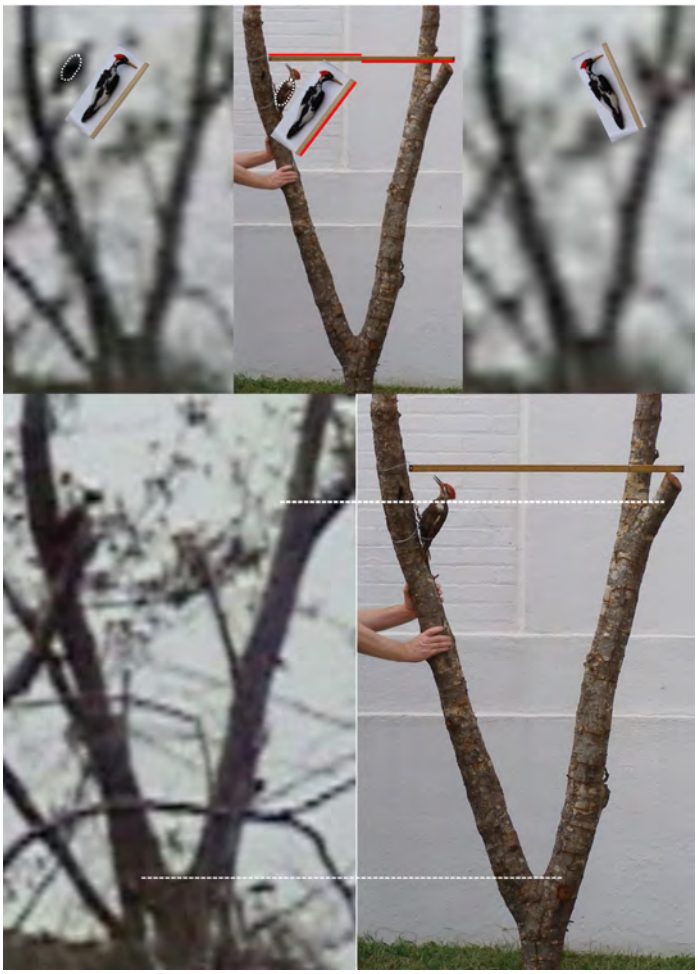

Fig. 3. Comparison of the woodpecker in the 2006 video with specimens of the large woodpeckers. As indicated by the dashed lines, two forks in the tree were used to scale the images. The Pileated Woodpecker specimen was mounted on the tree specimen along with a meter stick. The Ivory-billed Woodpecker specimen was photographed with a half meter stick that was used for scaling as indicated by the red lines. The woodpecker in the video was partially hidden by vegetation in the image on the lower left, but it was in full view during a short flight between limbs (top left). The outline of the body of the Pileated Woodpecker specimen is marked by a dashed curve that was copied without changing its size.

The largest of the male specimens (which is about the same size as the largest of the female specimens) was photographed with a half meter stick that was used for scaling in Fig. 3. If the neck and bill of that specimen were fully extended, the length would be near the maximum for the Ivory-billed Woodpecker. A dashed curve was used to mark the outline of the body of the Pileated Woodpecker specimen in Fig. 3; this curve was copied without modifying its size. The woodpecker in the video is much larger, in terms of length and body size, than the Pileated Woodpecker specimen and comparable in size to an Ivory-billed Woodpecker specimen that is near the maximum size for that species. The size alone is

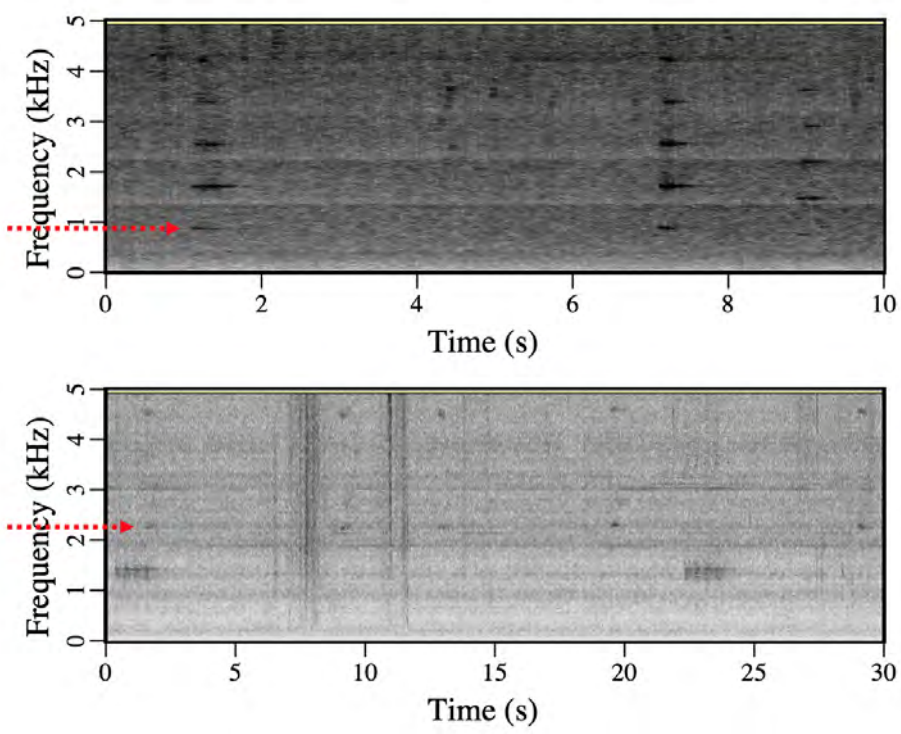

Fig. 4. Top: The fundamental frequency is less than 1 kHz for the apparent kent calls that were recorded in Florida.[5] Bottom: The fundamental frequency is greater than 2 kHz for the high-pitched calls that were captured in the 2006 video.

sufficient to rule out all species of the region except the Ivory-billed Woodpecker. Several additional characteristics and behaviors are consistent with that species but not the Pileated Woodpecker.

Avian artists study the field marks, body shapes and proportions, and behaviors of their subjects in intimate detail. After analyzing the 2006 video, Julie Zickefoose, whose depiction of an Ivory-billed Woodpecker had recently appeared on the cover of the January 2006 issue of the *Auk*, provided the following comments:[7]

> I like the head/neck/crest and especially bill to head proportions. They do not suggest Pileated Woodpecker to me—too massive, especially the large, long bill. The rared-back pose, long but fluffy and squared-off crest, and extremely long, erect head and neck suggest Ivory-billed Woodpecker. The flapping leap the bird takes to the right, across the two trunks, is very unusual, and unlike anything I've seen a Pileated Woodpecker do. The flight appears ponderous and heavy, and the wings altogether too long and thin for a Pileated Woodpecker. The bird overall just looks very large and heavy.

The image on the lower left in Fig. 3 shows the "rared-back pose, long but fluffy and

squared-off crest, and extremely long, erect head and neck."

The two large woodpeckers are superficially similar, but they belong to different genera and have substantial differences in behavior and body proportions. The Ivory-billed Woodpecker is one of the most massive woodpeckers in the world, and it has narrow wings that are suitable for high-speed flights to distant foraging sites. On the basis of this combination of characteristics, it is not surprising that, according to historical accounts, the Ivory-billed Woodpecker usually flaps it wings during short flights between limbs[2] and takes off into level flights with deep and rapid flaps.[16] The Pileated Woodpecker has a much lower body mass and broad wings that are suitable for moving around within a relatively small territory; it takes short flights between limbs and takes off into level flights nearly effortlessly. Appearing in Movie S1 (which plays at half speed) is the short flight in the 2006 video, which covered less than 1 m and is "unlike anything I've seen a Pileated Woodpecker do," according to Zickefoose. The deep and rapid flap is consistent with what would be expected for a woodpecker that has a high mass and narrow wings, but it is quite different from the flaps of Pileated Woodpeckers taking short flights in Movie S2 (which plays at half speed). The effects of camera motion and zooming have been removed in Movie S3, which shows a takeoff with deep and rapid flaps at full speed.

While perched, the large woodpecker in the video engaged in some behaviors that do not seem to be consistent with a Pileated Woodpecker but never engaged in other behaviors that are typical of that species. The effects of camera motion and zooming have been removed in Movie S4, which plays at full speed and shows the bird rotating around a branch while remaining in the "rared-back pose" that Zickefoose mentioned. This behavior does not seem to be consistent with the Pileated Woodpecker. I obtained the video footage appearing in Movie S5 while sitting in a kayak at distances of a few tens of meters from Pileated Woodpeckers that showed no sign of being alarmed. Arthur T. Wayne, a specimen collector who "encountered more than 200" Ivory-billed Woodpeckers in the 1890s,[14] left the following account:[2] "I saw and heard four Ivory-bills the day before in California Swamp, but could not get a shot because they were too wild, and couldn't be approached nearer than 300 or 400 yards." The perch tree was well beyond the range at which a Pileated Woodpecker would become alarmed but well within the range at which an Ivory-billed Woodpecker would become alarmed, according to Wayne's account. While perched, the large woodpecker in the video showed signs of being alarmed, including raising its crest and hiding behind a branch, but it never engaged in any of the typical behaviors of a non-alarmed Pileated Woodpecker going about its business early in the morning, such as foraging, calling, and drumming.

It has been suggested that the 2006 video shows a *Campephilus* woodpecker that was filmed in South America. It may be verified that this footage was obtained in the Pearl River swamp in Louisiana by inspecting video footage from a drone that was launched at the location from which the video was obtained (where trees that appear in the video were still recognizable) and then flown up to altitudes from which the rocket towers at Stennis Space Center and other landmarks were visible.[22] A movie that documents the events that occurred during the encounter is available at a data repository.[23] Immediately after the bird flew into the woods, I started recording with the video camera and turned the kayak

around in order to drift down the bayou in the direction the bird had flown. Several of the high-pitched calls were captured in that part of the video. After the calls seemed to stop, I backed the kayak into an observation position on the opposite side of the bayou. During the next several minutes, a few additional calls provided clues to the movements of the bird through the woods. Just before I noticed motion and zoomed the camera, the field of view was centered on the perch tree. Part of the context of the 2006 video is a series of five sightings that week that provided excellent views from close range of definitive field marks and flights and two other encounters in the same area during which kent calls were heard, once coming from two directions at the same time.

All recordings of known and putative calls of the Ivory-billed Woodpecker consist of simultaneously excited harmonics. Sonograms of three apparent kent calls that were obtained in Florida[5] and five of the high-pitched calls from the 2006 video appear in Fig. 4. The fundamental frequency is less than 1 kHz for each of the apparent kent calls (the sonograms of other known and putative kent calls are similar). The high-pitched alarm calls that Tanner described would be expected to consist of simultaneously excited harmonics that have a higher fundamental frequency than kent calls. The fundamental frequency of each of the high-pitched calls in Fig. 4 is greater than 2 kHz. The sonograms of those calls (which were twice observed coming from the direction of an Ivory-billed Woodpecker immediately after it became alarmed) are consistent with what would be expected for the alarm calls that Tanner described. There have been many reports of kent calls during the past several decades, but it does not appear that anyone else has reported the alarm calls of the Ivory-billed Woodpecker since the 1930s. During many encounters, an alarmed Ivory-billed Woodpecker might simply flush and seek cover without calling. The alarm calls might be given only under certain circumstances, such as near a nest (as in the 1930s) or to alert another bird of danger (as in the encounter illustrated in Fig. 1).

4. A Large Woodpecker in Flight that is not a Pileated Woodpecker

A short distance up the same bayou on March 29, 2008, I was keeping watch out over the treetops for Ivory-billed Woodpeckers from 23 m up in a tree that served as an observation platform. I noticed a large bird flying up the bayou in the distance and initially thought it was a Wood Duck (*Aix sponsa*) on the basis of its large size and high flight speed (there are historical accounts of Ivory-billed Woodpeckers being mistaken for ducks). As illustrated in Fig. 5, I saw two white stripes on the back and black leading edges and white trailing edges on the wings when the bird passed nearly directly below. These are definitive field marks of the Ivory-billed Woodpecker, but I was faced with an apparent paradox upon inspecting the video, which may be viewed at full speed in Movie S6. On the basis of historical accounts of a 'duck-like' flight, such as "the flight resembles that of a Pintail,"[2] the Ivory-billed Woodpecker was believed to have a duck-like wing motion in which the wings remain extended throughout the entire flap cycle, but the bird in the video clearly folds its wings closed in the middle of each upstroke. As illustrated in Movie S7 (which plays at half speed), the Pileated Woodpecker has a similar wing motion. Avian artists are very thorough

Fig. 5. Illustration of the view of the flyunder that appears in the 2008 video.[6] The two white stripes on the back and the black leading edges and white trailing edges on the wings were well seen from an ideal vantage point at close range and nearly directly above. The wings were folded closed in the middle of each upstroke. This diagnostic wing motion, which is well resolved in the video, is consistent with the two large woodpeckers but no other large bird (wingspan over 24 inches) of the region.

in researching their subjects. In a series of paintings of the two large woodpeckers in flight by Zickefoose,[24] the wings of the Pileated Woodpecker are correctly shown folding closed in the middle of the upstroke; in an accurate representation of conventional wisdom at the time, the wings of the Ivory-billed Woodpecker are shown remaining extended throughout the flap cycle. The paradox was resolved after discovering that a photo from the 1930s shows an Ivory-billed Woodpecker in flight at an instant when the wings were nearly folded closed.[7] Accounts of a duck-like flight evidently pertained to the flight itself rather than the wing motion.

Since the bird and its reflection from the surface of the bayou appear in the video, it was possible to determine positions of the bird along its flight path and estimate the wingspan and flight speed. As shown in Fig. 6, the horizontal position of the bird projected onto the surface of the bayou corresponds approximately to the apparent midpoint between the bird and its reflection. On March 30, 2010, Tommy Tuma and Wayne Higginbotham of the Louisiana Department of Wildlife and Fisheries assisted in obtaining a reference photo for estimating the wingspan. Some of the details of how the estimate was obtained using a 24-inch reference object are provided in Document S1. The size of the reference object is greater than the wingspan of the Belted Kingfisher (*Megaceryle alcyon*), which is the

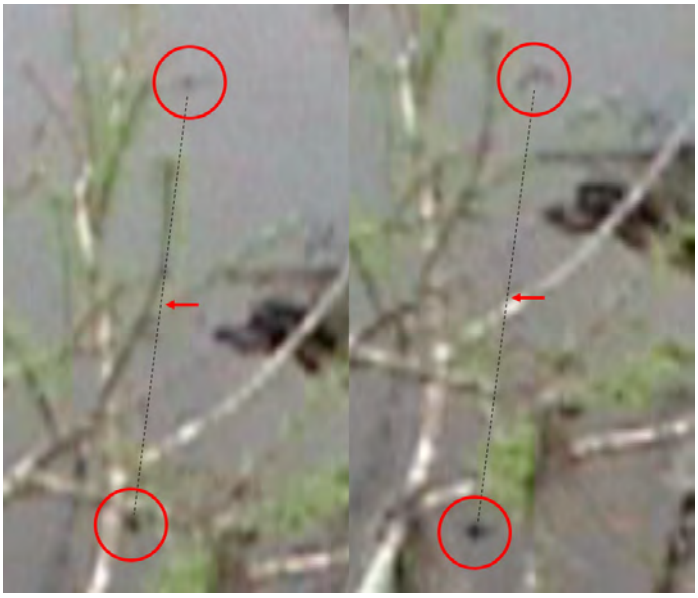

Fig. 6. Frames from the 2008 that were used to estimate the wingspan. The circles mark the locations of the bird and its reflection. The arrows indicate the approximate locations of the projection of the bird onto the surface of the bayou. Left: The wings are fully extended but poorly resolved. Right: The wings are well resolved but only partially extended. The lines between the images are vertical, but the video camera was not held perfectly level.

third largest (in terms of wingspan) bird of the region (behind the two large woodpeckers) that does not keep its wings extended throughout the flap cycle. As shown in Fig. 7, the reference object was held near where the bird flew past trees that were used to scale the reference photo relative to frames from the video.

A dashed rectangle with the same width as the reference object was added to the reference photo and then copied (without changing its size) onto frames from the video. In the frame from the video that appears in Fig. 8, the wings are well resolved but only partially extended. The wings fit within the rectangle when only partially extended, but it appears that they would not fit within the rectangle when fully extended. The wings are fully extended in a similar comparison appearing in Fig. 9. In that part of the video, the wings are not well resolved when fully extended, but it is clear after adjusting the contrast and brightness that the wingspan is well over 24 inches (and consistent with a large woodpecker). The two large woodpeckers are the only birds of the region with a wingspan over 24 inches that fold their wings closed in the middle of the upstroke. Birds are occasionally recorded outside of their normal ranges, but there are no records of any of the other large woodpeckers north of the Rio Grande. The range of the Ringed Kingfisher (*Megaceryle torquata*) extends just to the north of the Rio Grande, and there are two records in Louisiana. The dorsal field marks of this large kingfisher are similar to the dorsal field marks of the Belted Kingfisher, which appear in Fig. 7. There is no trace of those distinctive and prominent field marks in the video, even when it is enhanced.[10]

Fig. 7. Tommy Tuma holding a 24-inch reference object that was cut from a yardstick. Prominent white patches consistent with the white trailing edges on the dorsal surfaces of the wings of the Ivory-billed Woodpecker appear in the three frames from the video on the lower left, which show no trace of the distinctive and prominent field marks on the dorsal surfaces of the wings of the Belted Kingfisher that appears in the other image.

An ornithologist who specializes in woodpecker flight mechanics, Bret Tobalske, analyzed the 2008 video with an approach based on the horizontal and vertical motions of the wingtips that he had previously developed and applied to other woodpeckers.[25] On the basis of this analysis, which involves digitizing the motions of the wingtips (but does not require information on the wingspan), Tobalske concluded that the bird in the video is a large woodpecker and provided the following comments:[7]

> I am confident it is a large woodpecker. I base this conclusion on the small upstroke/downstroke span ratio and the pauses in mid-upstroke during which the bird holds its wings flexed in a 'bound' posture. This style of flight is consistent with Pileated Woodpecker, but I do not think that it rules out the bird being an Ivory-billed Woodpecker. Casual observers of a live bird in the field (e.g., Tanner) would likely miss the brief pauses even if they were present. There are two fields in which there is considerable white (or light gray) visible on the upper surface of the wings. Those patches of light-colored feathers would seem to be consistent with an Ivory-billed Woodpecker.

The many types of avian flight include cruising flight, level takeoffs and landings, swooping takeoffs and landings, short flights between limbs, flap-gliding flights, soaring, escape flights, stooping flights, and others. For the case of cruising flight, flap rate is amenable to statistical analysis, and the standard deviation is typically less than ten percent of the mean.[25–27] The large woodpecker in the 2008 video was in cruising flight. Only two large woodpeckers exist

Fig. 8. Top: The width of the white rectangle is the same as the length of the reference object. Bottom: The rectangle has been copied without changing its size onto an image from the video in which the wings were only partially open; this image was scaled using objects that appear in the video. Small tree branches that appear in the foreground in the lower image were removed to obtain the reference photo.

in the region, but the flap rate of the bird in the video is about ten standard deviations greater than the mean flap rate of the Pileated Woodpecker.[7] These facts are sufficient to rule out all species except the Ivory-billed Woodpecker. Several additional characteristics and behaviors are consistent with that species but not the Pileated Woodpecker.

As illustrated in Document S2, the flight speed was estimated using images of the bird and its reflection to determine positions of the bird at times that are separated by 4.38 s; the bird traveled 66.5 m during that interval for a flight speed of 15.2 m/s,[7] which is well above the range of 7.5 to 11.6 m/s that Tobalske reported for the Pileated Woodpecker.[25] As discussed in Movie S8, the prominent white patches on the dorsal surfaces of the wings, narrow shape of the wings, and swept-back appearance of the wings are consistent with the Ivory-billed Woodpecker but not the Pileated Woodpecker. As discussed in Ref. 10, it becomes apparent upon enhancing color, brightness, and contrast that the bird in the video has a black body and black leading edges on the dorsal surfaces of the wings, which are consistent with the Ivory-billed Woodpecker. A movie that documents that I was keeping

Fig. 9. Top: Similar to the bottom image in Figure 8 but for a frame from the video in which the wings are nearly fully extended but poorly resolved. Bottom: It is clear that the wingspan exceeds 24 inches when the brightness and contrast are adjusted.

watch out over the treetops and contains other context information (including an apparent double knock that is audible in the video shortly before the bird flew into view) is available at a data repository.[23]

5. Deep and Rapid Wingbeats and Loud Wing Sounds

Early in 2007, I visited the area where Hill and his colleagues had recently reported a series of sightings.[5] On January 19, I participated in a follow up to a report of an encounter with two Ivory-billed Woodpeckers late on the previous afternoon. I decided to flank around the area toward which the birds had been observed flying in hopes they were heading in the direction of a roost. I came upon two Ivory-billed Woodpeckers in the distance that were repeatedly making spectacular swooping flights. During one of the swooping flights, I had a clear view through binoculars of the dorsal surface of the right wing of one of the birds, which held its wings fixed during the flight. With a high-definition video camera mounted on the kayak paddles, I obtained more than 20 minutes of footage of swooping flights, takeoffs into

level flights, a double knock, and other behaviors.[6] Several events that appear in the 2007 video show field marks, body proportions, flights, and other behaviors and characteristics that are consistent with the Ivory-billed Woodpecker but no other species of the region. A video containing one such event would be strong evidence. It follows from basic concepts in probability that a video containing several such events (all obtained during one encounter) becomes more compelling as the number of events increases.[9] Three of the events in the 2007 video are among the five most compelling events. A movie that contains context information is available at a data repository.[23]

Both birds were briefly visible at the same time during an event that began 5:10 into the video,[6] when the first bird made an upward swooping landing with a long vertical ascent that appears in Movie S9 (which plays at full speed). As discussed in Movie S10, the body is black (including the belly), and the underwings appear mostly white. The bird ascended nearly vertically without flaps for about 1 s, which would correspond to about 5 m for a ballistic flight and an even greater distance if there was braking. This flight is consistent with Eckleberry's account of a landing with "one magnificent upward swoop." The combination of the field marks and the flight is not consistent with any species other than the Ivory-billed Woodpecker. During the upward swooping landing by the first bird, the second bird was perched on a horizontal branch near the trunk of a tree, which is consistent with an account by Tanner[2] that an Ivory-billed Woodpecker will occasionally "sit across a limb." As shown in Movie S11 (which plays at full speed), the second bird dives behind the trunk (or perhaps into a cavity) with a motion that is similar to an Ivory-billed Woodpecker diving into a cavity in the historical film. About 20 s later, both birds take off within a few seconds of each other into level flights with deep and rapid flaps. In Movie S12 (which plays at full speed), the takeoff of the second bird is compared with takeoffs into level flights by Pileated Woodpeckers and the closely-related Imperial Woodpecker (*Campephilus imperialis*).[28] The deep and rapid flaps of the bird in the video are similar to the deep and rapid flaps of the Imperial Woodpecker but quite different from the flaps of the Pileated Woodpeckers.

There are sounds from the wings during both of the takeoffs into level flight, which are visible and audible in Movie S13 (which plays at full speed; the first bird takes off in the lower right of the picture; the second bird takes off to the upper left of center; this full-quality movie may not play smoothly on older computers; it is best to view it on a large monitor with good speakers at full volume). The wing sounds and the deep and rapid flaps are consistent with the following account by Tanner:[2] "The wing-feathers of Ivory-bills are stiff and hard, thus making their flight noisy. In the initial flight, when the wings are beaten particularly hard, they make quite a loud, wooden, fluttering sound, so much so that I often nicknamed the birds 'wooden-wings'; it is the loudest wing-sound I have ever heard from any bird of that size excepting the grouse." As previously noted, the first bird appears to have a black body and underwings that are mostly white during the upward swooping landing. As discussed in Movie S14, additional field marks consistent with the Ivory-billed Woodpecker are evident just after the takeoff with deep and rapid wingbeats. The combination of the upward swooping landing, field marks, deep and rapid flaps, and wing sounds that are audible from a distance is consistent with the Ivory-billed Woodpecker

Fig. 10. Illustration by Michael DiGiorgio that compares upward swooping landings by Pileated and Ivory-billed Woodpeckers.[6]

but no other species of the region. Since the wing sounds were strong enough to be captured by the camera, the sound of the first bird taking off was probably audible to the second bird just before it took off. An interesting question is whether one bird might in some way take advantage of the wing sounds of another bird that it cannot see (e.g., to take off and join the other bird in flight).

6. A Landing with a Magnificent Upward Swoop

During a landing with a long vertical ascent[6] at 15:21 in the 2007 video, which plays at full speed in Movie S15, the view of the bird initially appears to be from the side, but mostly white underwings appear to be turned toward the camera after a long vertical ascent. It appears that the bird rotated about its axis during the ascent. A long vertical ascent would make such maneuvering possible, and there exists a film of the closely-related Magellanic Woodpecker (*Campephilus magellanicus*) maneuvering during a long vertical ascent.[29] An illustration of rotating about the axis during a long vertical ascent appears in Fig. 10,

which also shows how a Pileated Woodpecker typically swoops upward a short distance before landing on a surface that faces the direction of approach. There was a downward swooping takeoff followed by a long vertical ascent[6] at 24:37 that plays at half speed in Movie S16. The view is from the side during the downward swooping takeoff. The view is ventral during the vertically ascending landing. As in the landing at 15:21, the bird apparently rotated about its axis during the ascent before landing on a surface that does not face the direction of approach. As discussed in Movie S17, there is a frame just before the landing that shows a dark-colored body, light-colored underwings, a tail that projects behind the wings about the same distance as the width of the wings, and a body width that is a substantial fraction of the width of the wings. This combination of characteristics is consistent with the Ivory-billed Woodpecker but no other species of the region. While the bird was climbing after the landing, there were several flashes of white that are consistent with the white triangular patch that forms when the wings of an Ivory-billed Woodpecker are folded closed on the back.[6]

7. A Double Knock and other Distinguishing Behaviors

An event involving a double knock,[6] which began at 17:32 in the 2007 video, is shown at full speed in Movie S18. After taking two short flights, climbing upward, moving to the right, and moving back to the left, the bird perched upright, delivered a blow that produced a double knock, and then took off into a flight with rapid wingbeats that almost immediately transitioned into an upward swooping flight. Due to the distance to the bird, there is a brief delay between when the blow is visible and when the sound is audible. The Ivory-billed Woodpecker is the only woodpecker north of the Rio Grande that signals with double knocks. There do not appear to be any historical accounts of the type of flight that follows the double knock, but the burst of rapid and powerful wingbeats that made it possible to rapidly accelerate and swoop upward just after taking off is consistent with the Ivory-billed Woodpecker. The "stiff and hard" wing feathers that Tanner[2] described may be an adaptation for such flights. In addition to the double knock and the upward swooping flight, there were two other behaviors that do not seem to be consistent with any species other than the Ivory-billed Woodpecker. As discussed in Movie S19, the bird in the video repeatedly 'flirts' its wings, a frequent behavior of the Ivory-billed Woodpecker according to Tanner,[2] while moving from right to left. It would make sense that a massive woodpecker would frequently use its wings for balance while moving around in a tree, and the most massive woodpecker in the world, the Imperial Woodpecker, flirts its wings in the only 85 s of film that exists for that species.[28] As discussed in Movie S20, the bird in the video perched on its tail and rotated its body from side to side at two points in the video. Ivory-billed Woodpeckers repeatedly make those motions in the historical film.

While studying the double knock, I noticed that there appears to be only one thrust of the body. This observation led to an understanding based on the concept of a harmonic oscillator of how double knocks (and the descending series of knocks of other *Campephilus* woodpeckers) are produced and how they relate to the drumming that is typical of most

Fig. 11. Illustration of two successive swooping flights at 3:18 in the 2007 video. The exact flight paths are unknown, but the arrows indicate points at which the bird and its direction of flight are visible through gaps in the vegetation.

woodpeckers.[8] When a woodpecker perches upright, it is anchored by its feet and tail. The neck may be thought of as a spring with a restoring force that accelerates the head and bill toward the wood, where the bill rebounds after each impact. Drumming is driven by oscillations of the body that are tuned to the natural frequency range of the system. Double knocks are driven by a single impulsive thrust of the body. One of the supplementary movies of Ref. 8 shows a Pale-billed Woodpecker (*Campephilus guatemalensis*) giving a double knock that is driven by a single thrust of the body. Audio recordings of the double and multiple knocks of several *Campephilus* woodpeckers are also included in the supplementary material of Ref. 8.

8. Additional Events

Some additional events in the 2007 video are briefly discussed here for completeness. Another upward swooping landing at 5:44 is shown at full speed in Movie S21.[6] At 2:02, there was a downward swooping takeoff followed by a long horizontal glide[6] that is consistent with the following account by Audubon:[14] "The transit from one tree to another, even should the distance be as much as a hundred yards, is performed by a single sweep, and the bird appears as if merely swinging from the top of the one tree to that of the other, forming an elegantly curved line." The bird is hidden during much of the flight, but it occasionally comes into view through openings in the vegetation during the first part of the flight in Movie S22 (half speed). A flash of white from the underwings is visible in the reflection from the water in Movie S23 (half speed). At 4:16, there was a downward swoop followed by a short upward swoop and landing in Movie S24 (full speed). As discussed in Movie

S25, the appearance of the dorsal surface of the right wing is consistent with an Ivory-billed Woodpecker just before the upward swoop, and a feature that resembles a thin dark trailing edge on the underside of the right wing apparently corresponds to vegetation.

Appearing in Movie S26 (full speed) is an upward swooping landing with a long vertical ascent at 3:18 that is immediately followed by a downward swooping takeoff. This event is representative of repeated swooping flights by both of the birds that were observed early in the encounter. As illustrated in Fig. 11, the bird is visible through gaps in the vegetation at only a few points along the flight paths. During the ascent, two 'spring-like' sounds are clearly audible with headphones. The source of the sounds is unknown, but it is conceivable that two closely-spaced sounds could be generated during a sudden change of direction at the beginning of an ascent when (1) the wings flex at maximum stress and (2) the stress is relaxed at the end of the acceleration. As would be expected for a distant bird, there is a brief delay between when the flight maneuver occurs and when the sounds are audible. If the sounds do indeed come from the wings, they could be the result of a rather unique combination of characteristics and behaviors of the Ivory-billed Woodpecker, which includes high flight speed, high mass, narrow wings, "magnificent" swooping flights,[15] and "stiff and hard" wing feathers.[2] Similar spring-like sounds are faintly audible at 1:07 (Movie S27), 3:06 (six seconds after a downward swooping takeoff that begins in the lower center of the picture in Movie S28), 9:29 (Movie S29), and 17:57 (25 seconds into Movie S18 just before the woodpecker in the double knock event comes into view while climbing).

9. Discussion

The five most compelling events in the videos show birds with field marks, body proportions, flights, and other behaviors and characteristics that are consistent with the Ivory-billed Woodpecker but no other species of the region. Previous analysis of each of the three videos is fortified here with additional results. The woodpecker in the 2006 video was perched on a tree that facilitated accurate scaling of images from the video relative to reference photos of specimens of the two large woodpeckers. The bird was in full view when taking a short flight between limbs, and it is comparable in size to an Ivory-billed Woodpecker specimen that is near the maximum size for that species. It is therefore larger than any Pileated Woodpecker. The woodpecker in the 2006 video has several additional behaviors and characteristics that are consistent with the Ivory-billed Woodpecker but not the Pileated Woodpecker. The bird in the 2008 video folds its wings closed in the middle of each upstroke, and it has a wingspan of well over 24 inches. The two large woodpeckers are the only species of the region that are consistent with that combination of wing motion and wingspan. An expert on woodpecker flight mechanics previously concluded that the bird in the 2008 video is a large woodpecker on the basis of an analysis of the wingtip motion that does not require knowledge of the wingspan. After concluding that the bird in the video is a large woodpecker, the conclusion that the Ivory-billed Woodpecker is the only plausible explanation then follows from flap rate statistics. The woodpecker in the 2008 video has several additional characteristics that are consistent with the Ivory-billed Woodpecker but not the Pileated Woodpecker. One of

the events in the 2007 video begins with a combination of a landing with a magnificent upward swoop and field marks that is consistent with the Ivory-billed Woodpecker but no other species. Both of the birds that appear in the event take off (within a few seconds of each other) with deep and rapid wingbeats and wing sounds that are loud enough to be audible from a distance. The combination of the wingbeats and the wing sounds is consistent with the Ivory-billed Woodpecker but no other species.

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