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The Role of Acoustics in the Conservation of the Ivory-billed Woodpecker (*Campephilus principalis*)

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The Ivory-billed Woodpecker (*Campephilus principalis*) is an iconic species that has survived in barely detectable numbers for the past 100 years, during which it has been feared extinct only to be rediscovered several times. The most recent rediscovery was announced in an article that was featured on the cover of *Science* in 2005. The persistence of the Ivory-billed Woodpecker became controversial when ornithologists were unable to obtain a clear photo for documenting this ultra-elusive bird during multi-year searches at sites in Arkansas and Florida, where they had several sightings and were convinced these birds were present. Audio recordings of 'kent' calls and double knocks were obtained at both sites, but such recordings are not regarded as conclusive evidence of persistence. A debate on this issue that took place in *Science* and *Nature* focused on relatively weak video evidence obtained in Arkansas but excluded three videos obtained in Louisiana and Florida that show flights, field marks, and other behaviors and characteristics that are consistent with the Ivory-billed Woodpecker but no other species of the region. Kent calls were recorded in the 1930s, when other types of vocalizations were observed but not recorded, including a high-pitched alarm call. On two occasions in Louisiana, high-pitched calls were observed coming from the direction of an alarmed Ivory-billed Woodpecker, and several of them were recorded. The spectrograms of the high-pitched calls and all other known and putative vocalizations of the Ivory-billed Woodpecker consist of simultaneously excited harmonics. A harmonic oscillator model has been used to draw a connection between the drumming that is typical of most woodpeckers and the double knocks of the Ivory-billed Woodpecker and other *Campephilus* woodpeckers. Drumming corresponds to periodic forcing; double knocks correspond to impulsive forcing, and a single thrust of the body is sufficient to produce two impacts of the bill in rapid succession. The audio recordings from Arkansas and Florida were obtained with single microphones. A horizontal array of microphones would make it possible to detect weaker sounds and determine the directions of sources. This approach has the

potential to lead to the discovery of a nest, and it might be more effective if the array is placed above the treetops, where sounds might propagate to longer ranges.

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

The Ivory-billed Woodpecker (*Campephilus principalis*) is an iconic species with a massive white bill, striking field marks, fascinating behaviors, and a compelling history.[1,2] During the past 100 years, this incredibly elusive bird has repeatedly been thought to be extinct only to be rediscovered. In the 1930s, a film, acoustic recordings, and photos, such as those appearing in Fig. 1, were obtained during a study at the last known nests in the Singer Tract in Louisiana.[3,4] In 2005, the announcement of the most recent rediscovery in the Big Woods of Arkansas[5] was the first published report of sightings by ornithologists in several decades. Many reports of sightings had been dismissed during the preceding 50 years, but this time several 'well-prepared' observers (defined here to be observers who are experienced and skilled at identifying birds in the field, cognizant of the field marks and sounds of the Ivory-billed Woodpecker, and acclimated to southern swamp forest habitats and the species that regularly occur in them) reported sightings during a search that was led by an ornithologist with a stellar set of credentials. During a career that began with getting an education at Harvard and Princeton, John Fitzpatrick discovered seven new species of

Fig. 1. Photos of Ivory-billed Woodpeckers that were obtained by James Tanner in 1935. The field marks include a massive white bill, two white stripes on the back, and white trailing edges of the dorsal surfaces of the wings (which form a white triangular patch on a perched bird). The male has a bright red crest. The head of the female is all black. These photos are in the possession of the U.S. Fish & Wildlife Service and are in the public domain (https://www.fws.gov/ivorybill/photoalbum/).

birds in the Amazon, helped create a national wildlife refuge to protect the habitat of the Florida Scrub-Jay (*Aphelocoma coerulescens*), and served as curator of birds at the Field Museum in Chicago. While leading the search in Arkansas, he was the director of the Cornell Laboratory of Ornithology, which had previously conducted the study in the Singer Tract.

Being featured on the cover of *Science*, the rediscovery of the Ivory-billed Woodpecker was perhaps the most exciting news in the history of conservation. It motivated searches that followed up on reports of sightings at locations in other states. During the years that followed, several sightings were reported in the Choctawhatchee River swamp in Florida[2,6] and the Pearl River swamp in Louisiana,[7–11] but 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. Reports on the status of this issue that appeared in *Science*[12] and *Nature*[13] focused on relatively weak evidence that was presented in the original paper,[5] provided platforms for critics to air unsupported opinions, mentioned that a non-scientist had faked a photo, and stated that no new evidence had been obtained; there was no mention of new evidence from Louisiana and Florida that is stronger than any other evidence that has been obtained during the past several decades.[7–11] After being exposed to biased negative reports but not the strongest evidence, the science community lumped the rediscovery of the Ivory-billed Woodpecker into the same category as cold fusion.

Given the difficulty of documenting the Ivory-billed Woodpecker, it is worthwhile to explore every potential tool for locating these birds. This paper discusses the 'kent' calls that were recorded in 1935, other vocalizations, double knocks, acoustic recordings that were obtained in recent years, and a strategy involving an array of microphones that might be useful for locating a nest. A section on the acoustics material follows a section that provides background information on the Ivory-billed Woodpecker, some of which is excerpted from Refs. 7–11.

2. Background Information

The purpose of this section is to provide: (1) insights into why the Ivory-billed Woodpecker has a remarkable history of elusiveness; (2) a summary of the body of evidence for its persistence; and (3) a discussion of decades of folly and politics that have undermined its conservation. A good starting point for evaluating the evidence would be video footage of a large bird in flight that was obtained in Louisiana in 2008. The bird in the video was identified in the field as an Ivory-billed Woodpecker on the basis of definitive field marks, which (as the video documents) were observed from a favorable vantage point (nearly directly above) at close range. The woodpecker-like flap style (the wings are folded closed in the middle of each upstroke) is consistent with a large woodpecker but none of the other large birds of the region (as confirmed by an expert on woodpecker flight mechanics who analyzed the video). The Ivory-billed Woodpecker and the Pileated Woodpecker (*Dryocopus pileatus*) are the only large woodpeckers of the region. Since the flap rate is about ten standard deviations greater than the mean flap rate of the Pileated Woodpecker, there is

only one possible explanation for the bird in the video. The high flight speed, narrow wings, white patches on the wings, and swept-back appearance of the wings are also consistent with the Ivory-billed Woodpecker but not the Pileated Woodpecker.

2.1. *Elusiveness*

The following facts could be used to make a case that the Ivory-billed Woodpecker is the most elusive bird in the world: (1) it has been feared extinct only to be rediscovered several times; (2) nobody has ever managed to obtain a clear photo without knowing the location of an active nest or roost cavity; (3) nobody has ever managed to obtain a clear photo away from a nest even when the location of the nest was known; (4) none of the numerous sightings that have been reported during the past several decades is supported by a clear photo; (5) ornithologists were unable to obtain a clear photo during multi-year searches at sites in Arkansas and Florida where they were convinced these birds were present; and (6) it is a species of great interest in a region that is easily accessible to a large number of bird watchers. According to an analysis based on a set of factors related to behavior and habitat,[8,10] it must take millions of times longer on average to obtain a photo of an Ivory-billed Woodpecker than it would take to obtain a photo of a hypothetical 'baseline' species of comparable rarity that has more typical behaviors and resides in a more typical habitat. The analysis is based on the model,

$$E = \frac{A}{B}\sigma, \tag{1}$$

where E is the expected waiting time for obtaining a photo, A is the area of the habitat that must be searched, B is the net area that is searched per unit time along all search paths, and σ is a dimensionless parameter that depends on habitat and behavior. Applying the same model to the baseline species, we obtain

$$\frac{E}{E_0} = \frac{A}{A_0}\frac{B_0}{B}\frac{\sigma}{\sigma_0}, \tag{2}$$

where the subscripted quantities correspond to the baseline case.

Visibility is typically limited to a few tens of meters in the vast swamp forest habitats of the Ivory-billed Woodpecker, which typically cover on the order of 100 km^2. In the baseline habitat, which covers on the order of 1 km^2, visibility is good out to hundreds of meters (the extra factor of $\sim$10 in distance corresponds to an extra factor of $\sim$100 in area). The geometric factors (area of the habitat and visibility within the habitat) account for a factor of $\sim 10^4$ in Eq. (2), but there are other factors related to habitat that affect B. Rare birds are discovered on a regular basis, usually as a result of a large community of bird watchers providing good coverage over various types of habitat, with someone occasionally getting lucky; however, bird watchers rarely visit the interiors of southern swamp forests, which have relatively low species diversity to attract them[2] and several factors to discourage them (e.g., many bird watchers are reluctant to risk being accidentally shot by venturing into habitats that are heavily hunted). It is difficult to follow search paths through thick vegetation and

flooded areas in southern swamp forests. It is easy to follow search paths in the baseline habitat, which gets good coverage by bird watchers. On the basis of differences between the habitats in terms of size, visibility, coverage by bird watchers, and difficulty of following search paths, we obtain

$$\frac{E}{E_0} \gg 10^4 \frac{\sigma}{\sigma_0}. \tag{3}$$

During the study in the Singer Tract, it was established that Ivory-billed Woodpeckers fly long distances from the nest or roost to forage. This non-territorial behavior is consistent with sporadic reports of sightings "where no one has been able to find the birds subsequently."[14] The Ivory-billed Woodpecker lacks conspicuous behaviors (such as loud and frequent calls) according to the following accounts by Allen and Kellogg:[3]

> They are not noisy except when disturbed.
>
> Their voice does not carry nearly as far as that of the Pileated Woodpecker.
>
> In the big trees which they normally frequent they are easily overlooked.
>
> We had hunted for three days for this particular pair of birds without ever hearing them, even though we were frequently within three hundred yards of the nest, which we finally found because we happened to be within hearing distance when the birds changed places on the nest.
>
> We camped for five days within three hundred feet of one nest and, except when the birds were about to change places on the nest or were disturbed, seldom heard them.

While collecting specimens in the 1890s, Arthur T. Wayne "encountered more than 200" Ivory-billed Woodpeckers.[14] His account that follows indicates that this species is exceptionally wary:[4]

> 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.

John James Audubon also indicated that the Ivory-billed Woodpecker is a wary species.[4] A bird that lacks conspicuous behaviors may not be detected until there is a close approach, but a wary bird may move away from the search path before it can be detected. A wary bird may vanish into cover before it is possible to obtain a photo. After having an initial sighting of a bird that forages within a relatively small territory, it should be possible to obtain a photo by waiting for a favorable opportunity to arise in the same area. After a wary bird is flushed at a location far from its nest or roost, there may be only a few seconds to obtain a photo. If the opportunity is missed, the bird may never return to that location. In a swamp forest, there are many places for a wary bird to seek cover, and it may be difficult to maneuver into a position for an unobstructed photo. The baseline species has conspicuous behaviors, is non-wary, and forages within a relatively small territory. On the

basis of differences between various factors related to behavior and habitat, we conclude that $\sigma \gg \sigma_0$ and that the expected waiting time for obtaining a photo of an Ivory-billed Woodpecker must be several orders of magnitude greater than it is for the baseline species.

After discovering a remnant population of Ivory-billed Woodpeckers in Cuba in 1948,[15] John Dennis continued to search for this species in the mainland part of its range and had sightings in Florida in 1951[16] and Texas in 1966.[17] The waiting time analysis is consistent with the following comments that Dennis made in a 1985 letter:[18]

> It takes a couple of years to search out and find the Ivorybill in only a single swamp.
>
> It is next to impossible to obtain photographs of an Ivorybill in a southern swamp unless a nesting site is discovered.

The relationship between the Ivory-billed Woodpecker and birds with more typical behaviors and habitats is somewhat analogous to the relationship between the neutrino and other subatomic particles. Physicists understand that the neutrino is an exceptional case and that it would be futile to attempt to detect them with approaches that are effective for detecting protons, neutrons, and electrons. Even without the waiting time analysis, it is clear from historical facts that the Ivory-billed Woodpecker is an exceptional case and that ideal evidence might not be obtained in time to make a difference in the conservation of this critically endangered species. In declining to consider the video evidence from Louisiana and Florida for publication, however, the editor of a leading ornithology journal made the comment, "People get great photos of extremely rare birds all the time," which indicates a lack of an understanding of the history, habitats, and behaviors of the Ivory-billed Woodpecker. There is no logical reason to require a specific type of evidence, and we already have other types of evidence (discussed in the three subsections that follow) that can be explained only in terms of the Ivory-billed Woodpecker.

2.2. *Sightings by Multiple Observers*

The Ivory-billed Woodpecker is a large bird with distinctive and prominent field marks and remarkable flights. All of these characteristics are advantageous to identifying birds. When viewed at the same distance, a larger bird may be easier to identify than a smaller bird for the same reason that binoculars are useful for identifying birds. Another way in which size can be a factor is that larger birds tend to have less rapid movements than smaller birds. The Ivory-billed Woodpecker has two prominent white stripes on the back and bold black and white markings on the wings. The only other large woodpecker of the region, the Pileated Woodpecker, does not have dorsal stripes and has a different pattern of black and white markings. On both surfaces of the wings (dorsal and ventral), the Ivory-billed Woodpecker has white trailing edges, while the Pileated Woodpecker has black trailing edges.

No flights appear in the 1935 film, but the Ivory-billed Woodpecker has a flight that is "graceful in the extreme" according to Audubon[14] and rapid wingbeats according to Tanner,[4] and there is an account by Eckleberry[19] of a landing "with one magnificent upward swoop." None of the flights of the Pileated Woodpecker are consistent with these accounts,

which suggest that the Ivory-billed Woodpecker has remarkable flights that would catch the attention of an experienced bird watcher. Despite a superficial similarity, the two large woodpeckers have markedly different physical characteristics and foraging strategies that correlate with different types of flight. The Pileated Woodpecker tends to forage within a relatively small territory. It has a lower mass and broader wings than the Ivory-billed Woodpecker; these characteristics are favorable for making frequent short flights within a foraging territory. The Ivory-billed Woodpecker is one of the most massive woodpeckers in the world, and it has narrow wings that are favorable for long flights at high speed to distant foraging sites. The relatively high mass and narrow wings of the Ivory-billed Woodpecker are not favorable for making frequent short flights; this bird usually needs to flap its wings during short flights between limbs, according to Tanner.[4]

During the searches in Arkansas and Florida, which were led by ornithologists, John Fitzpatrick and Geoff Hill, there were sightings by several well-prepared observers (including Hill), who spent long periods of time in the field observing the Pileated Woodpecker and other common species on a daily basis. It is not plausible to dismiss those sightings as a series of mistakes. This is a powerful form of evidence for the persistence of the Ivory-billed Woodpecker.

2.3. *Multiple Sightings by One Observer*

A report of multiple sightings by one observer is a different type of evidence than a report of the same number of sightings by multiple observers each having one sighting. An advantage of having multiple observations of a species is that each encounter may be an opportunity to become more proficient at identifying that species on the basis of field marks, vocalizations, and behaviors. The steepest part of the learning curve is at the beginning, and none of the participants in the searches in Arkansas, Florida, and Louisiana had previously observed an Ivory-billed Woodpecker in the field. During a five-day period in 2006, I had five sightings and twice heard kent calls in a concentrated area along English Bayou in the Pearl River swamp, which appears in Fig. 2. That series of encounters was preceded by my first sighting 1.3 km down the same bayou two weeks earlier. During sightings on February 16 and 17, the field marks on the dorsal surfaces of the wings were observed as clearly as indicated in the illustrations appearing in Fig. 3. On February 16, I had an excellent view from close range of the bold white patches on the trailing edges of the dorsal surfaces of the wings as the bird flew into cover with rapid wingbeats that were consistent with an account by Tanner. I heard three kent calls after returning to the area late that afternoon. During one of three sightings on February 17, I had an excellent view of the same features on the dorsal surfaces of the wings as the bird glided low across the bayou in a flight that was 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."

On February 18, I heard kent calls coming from two directions at the same time. As illustrated in Fig. 4, I silently maneuvered the kayak close to the first bird, which was

Fig. 2. A photo of the Pearl River swamp in Louisiana that was obtained with a drone. Video evidence was obtained along English Bayou near the left edge of the photo in 2006 and near the center of the photo in 2008. The East Pearl River near the right edge of the photo is part of the border with Mississippi.

calling from behind a fallen tree on the bank, as an American Robin (*Turdus migratorius*) was scolding from above. While I waited for the first bird to move into view with a still camera in hand (a day before obtaining a video camera), kent calls started coming from the second bird directly behind me on the opposite side of the bayou. When the second bird apparently saw me near the first bird, harsh scolding calls (which were consistent with a call that was observed but not recorded in 1935) started coming from the direction of the second bird. A series of high-pitched calls then started coming from the same direction, and the first bird stopped calling. At the same location on February 20, I came upon an Ivory-billed Woodpecker that was briefly perched on a broken-off tree at close range. As it flew into the woods, the same high-pitched calls started coming from its direction. This time, I had a video camera and recorded several of the high-pitched calls,[7] which seem to be consistent with an account by Tanner of a high-pitched alarm call of the Ivory-billed Woodpecker.[4] On two occasions, I heard those calls coming from the direction of an alarmed Ivory-billed Woodpecker.

The Pileated Woodpecker has a dark-colored eye that blends in with a line of black plumage. During the sighting on February 20, it gave me an eerie feeling to see the light-colored eye of an Ivory-billed Woodpecker, which stood out prominently in the surrounding black plumage and gave the impression that it was staring at me. After having no sightings in the Pearl River swamp in 2007, I had my final two sightings there in 2008. A short distance up the same bayou on March 29 of that year, I saw the white dorsal stripes and

Fig. 3. Artistic recreations of sightings in the Pearl River swamp in 2006.[10] Ivory-billed Woodpeckers are painted onto photos of the locations where sightings occurred on February 16 (top) and 17 (bottom).

the black leading edges and white trailing edges on the dorsal surfaces of the wings as an Ivory-billed Woodpecker flew nearly directly below my observation position about 23 m above the bayou, as illustrated in Fig. 5. During a visit to a site in Florida where Hill and his colleagues had recently had a series of sightings,[2,6] I had an encounter on January 19, 2007, with a pair of Ivory-billed Woodpeckers that were repeatedly making spectacular swooping flights that must have been the types of flights that inspired accounts by Audubon and Eckleberry.

Fig. 4. Illustration of an encounter with two Ivory-billed Woodpeckers in the Pearl River swamp on February 18, 2006.[10] With a still camera in hand, I sat in the kayak as a steady stream of kents came from the first bird, which was hidden behind the fallen tree at close range. A few minutes later, kents started coming from the second bird, which was behind me and on the opposite side of the bayou.

It is not plausible to dismiss my ten sightings as a series of mistakes, and three of the encounters are supported by video footage of birds with flights, field marks, and other behaviors and characteristics that are consistent with the Ivory-billed Woodpecker but no other species of the region. It would be fair to ask how one person managed to: (1) have five sightings in five days (nobody else has had a comparable series of sightings in recent decades) and a total of ten sightings; (2) be the first to have encounters with pairs in two states since Arthur Allen[3] had encounters with pairs in Florida in 1924 and in Louisiana in 1935 (the same states where my encounters occurred); and (3) obtain videos during three of the encounters that each contains stronger evidence than anything else that has been obtained during the past several decades. A favorable set of factors helped to even the odds

Fig. 5. Illustration of the flyunder in the Pearl River swamp on March 29, 2008, as viewed from my observation position 23 m above the bayou.[10] Before the 2008 video was obtained, it was believed that the Ivory-billed Woodpecker keeps its wings extended throughout the flap cycle. As shown here, the bird in the video folds its wings closed during the middle of the upstroke.

in my search for a bird that is arguably the most elusive in the world. In order to have a reasonable chance of finding an Ivory-billed Woodpecker, it is necessary to spend long periods of time (months and perhaps even years) in appropriate habitat. Since my employer has an office at the Stennis Space Center, which borders on the Pearl River swamp, I had an opportunity to conduct a long-term search while holding down a full-time job. I typically spent a few hours in the field early in the morning before going to work. It would be difficult to make the decision to dedicate substantial resources and time to a search at a site where there is no indication that Ivory-billed Woodpeckers may be present, but a sighting had recently been reported in the Pearl River swamp.

In the aftermath of Hurricane Katrina, which hit a few months before my search began, there were many standing dead trees (which are favorable for woodpecker foraging) in the Pearl River swamp. I was fortunate that two Ivory-billed Woodpeckers were frequenting an

area along English Bayou that is only 3.3 km by kayak from the boat launch at Stennis Space Center. If those birds had instead been using an area only a few hundred meters from that waterway, I might have missed them and given up after the first year of searching. For a period of several years leading up to the search, I honed my skills for identifying birds in terms of field marks, vocalizations, and behaviors during numerous intensive bird watching trips in North America, South America, Europe, and Australia. Having spent a great deal of time in swamp forests while growing up in Florida, I was probably more willing than a typical bird watcher to venture alone deep into such habitats. In 2002, there was an unsuccessful search in the Pearl River swamp that followed up on a report of a sighting of a pair of Ivory-billed Woodpeckers. None of the participants had ever observed an Ivory-billed Woodpecker or knew of an effective approach for trying to find them. During the pioneering search in Arkansas a few years later, valuable lessons were learned about using kayaks to silently move through appropriate habitat, which makes it possible to get closer to a wary bird before being detected. I took advantage of those lessons during my search.

I applied my experience as a scientist, problem solver, and independent thinker before, during, and after the search. I decided to conduct a search after concluding that it was not plausible to dismiss the sightings in Arkansas as a series of mistakes, and I was never discouraged by naysayers after the issue became controversial. Analyzing video evidence requires logical reasoning and an understanding of topics that were already familiar to me (such as probability and statistics) and topics that required researching the literature (such as avian flight mechanics). After having a series of sightings of Ivory-billed Woodpeckers that flushed and then rapidly disappeared into cover before there was time to set down the kayak paddles and grab a camera, I got the idea to mount a high-definition video camera on the paddles. With the setup shown in Fig. 6, it is possible to aim the camera at a bird almost instantly while paddling a kayak. The camera is kept recording at all times, and the paddles are used to aim the camera. I was using the paddle-cam during an encounter with a pair in 2007. After having encounters with Ivory-billed Woodpeckers that rapidly disappeared into thick vegetation, I got the idea to use tall trees as observation platforms. These birds are known to fly long distances over the treetops to foraging sites. I was hoping to spot a distant Ivory-billed Woodpecker in flight that would remain in view for more than just a few seconds (as they typically do when flushed) and perhaps reveal the location of a nest. I was using this approach when the third and final video was obtained during my tenth and final sighting in 2008.

Another factor in the success of my search is a determination to persist year after year on a problem that is challenging but worthy of such an effort. This factor came into play while pursuing the goal of extending the parabolic equation method[20–22] to efficiently provide accurate and stable solutions to wave propagation problems in ocean acoustics and seismology in environments with lateral variations and layers that support shear waves. When I started working on that problem in 1985, there were many who thought it was impossible. I was totally dedicated to the search and willing to do whatever it took to find the Ivory-billed Woodpeckers that had eluded others in the Pearl River swamp. An incident that occurred during the second year of the search exemplifies the level of my

Fig. 6. High-definition video camera mounted on kayak paddles.[8] The paddles may be used to aim the camera at a bird almost instantly with this setup.

determination. As the anniversary of the series of sightings in February 2006 approached, I planned to monitor the area to see if the birds might return, but I fell and suffered a complete fracture of my left radius on February 13, 2007. Refusing to allow the injury to stop me, I managed to paddle the kayak up English Bayou to the old hot zone a week later. I paid a hefty price for that decision. The broken ends of the bone moved out of alignment during the kayak ride, and surgery was required to install the plate and screws appearing in Fig. 7.

After going five years without a sighting, I transferred back to our main office in Washington in 2013, but I continued to make brief visits to the Pearl River swamp each year. In 2016, I started using drones to inspect habitats, locate trees that are dying or have signs of woodpecker foraging, and search for Ivory-billed Woodpeckers.[23] In March 2021, I heard a double knock near the location where the 2006 video was obtained. An apparent double knock is not conclusive, but it was the first sign in more than a decade that Ivory-billed Woodpeckers might be in the area. A few months later, I did some drone flights over the area and found a massive dying tree that would be ideal for Ivory-billed Woodpecker foraging, according to historical accounts.

2.4. *Video Evidence*

The strongest evidence that came out of the search in Arkansas was a series of sightings by multiple observers that is discussed in Sec. 2.2, but video evidence was also presented in the paper that announced the rediscovery of the Ivory-billed Woodpecker.[5] Various opinions have been expressed about that video, which was the focus of a debate on the persistence of the Ivory-billed Woodpecker that took place in *Science* and *Nature*. Some opinions should

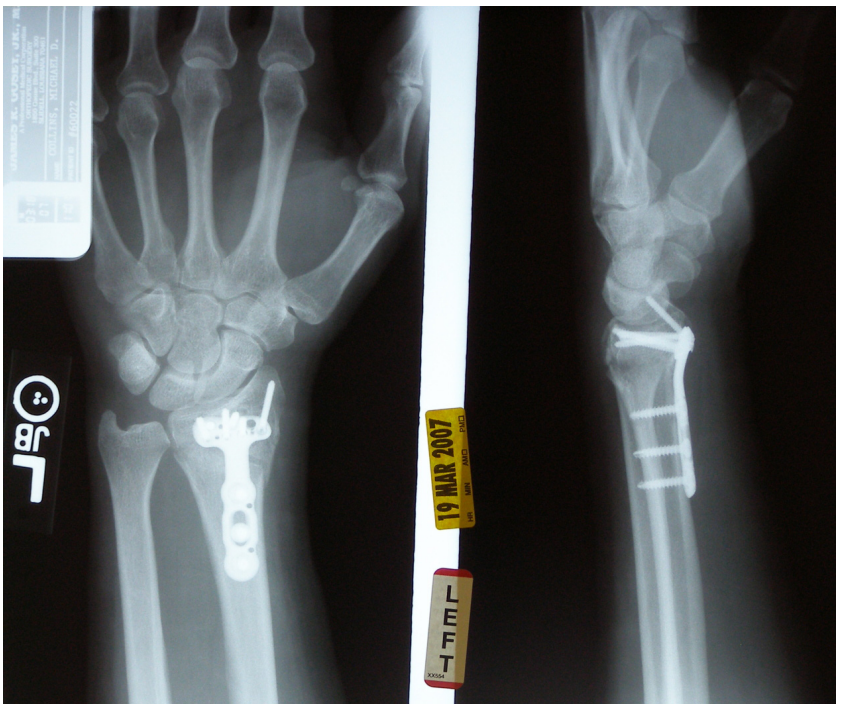

Fig. 7. I kayaked back to the 2006 hot zone a week after fracturing my left radius. The broken ends of the bone moved out of alignment, and a plate and screws had to be surgically installed.

carry more weight than others. Among living ornithologists, Geoff Hill has a unique set of credentials that includes discovering Ivory-billed Woodpeckers in Florida, having a sighting, publishing his findings in an avian conservation journal,[6] and writing an authoritative book on this species.[2] Independent of his work on the Ivory-billed Woodpecker, Hill received the 2014 William Brewster Memorial Award, which is given by the American Ornithologists' Union to the author of the most meritorious body of work on birds of the Western Hemisphere during the preceding ten years (John Fitzpatrick received this award in 1985). Hill expressed the following opinion of the video that was obtained in Arkansas:[12] "In retrospect, the Luneau video may loom as one of the most unfortunate things to ever happen to the [Cornell] Laboratory of Ornithology." After studying the videos that were obtained in Louisiana and Florida, Hill concluded that they are "very convincing," but this evidence was excluded from the debate that took place in *Science* and *Nature*. The videos are summarized here and discussed in greater detail in Refs. 7–11. Discussions of the videos are also available in lecture format.[24] The raw footage is available for download at a data archive.[25]

Immediately after the sighting on February 20, 2006, I started recording with a Sony DCR-HC36 standard video camera. I tracked the movements of the high-pitched calls while drifting down the bayou in the kayak. After the calls stopped, I backed the kayak into an observation position near the opposite bank. About ten minutes into the video, I noticed motion deep in the woods in the direction where the last calls had originated. I tried to

find the bird in the viewfinder of the camera and in a pair of binoculars. Although I never managed to spot the bird, I kept the camera aimed in the direction of the motion and obtained footage of a large woodpecker perched on a tree, climbing upward, taking a short flight between limbs, and then taking off into a longer flight. Julie Zickefoose, an avian artist whose paintings of the Ivory-billed Woodpecker have appeared on the covers of the January 2006 issue of the *Auk* (a leading ornithology journal) and both editions of Ref. 1, analyzed the 2006 video using her experience in studying the Ivory-billed Woodpecker. Zickefoose noticed several characteristics and behaviors that are consistent with the Ivory-billed Woodpecker but not the Pileated Woodpecker and provided the following assessment:[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.

Part of the perch tree, which includes two forks that facilitated scaling, was used in the size comparison in Fig. 8. The bird in the video appears to be larger than a Pileated Woodpecker, which would leave the Ivory-billed Woodpecker as the only possibility, and it has several characteristics that are consistent with that species but not the Pileated Woodpecker. The flight between limbs covered less than a meter. Pileated Woodpeckers make such flights nearly effortlessly, but the bird in the video required an unusual deep and rapid flap, which is consist with what would be expected for a massive woodpecker with narrow wings and with Tanner's account that the Ivory-billed Woodpecker needs to flap its wings during short flights between limbs. This flight, which does not seem to be consistent with the Pileated Woodpecker according to Zickefoose, is compared with short flights by that species in Movie S3 of Ref. 8.

I had intended to use a high-definition video camera during the observation session when the flyunder occurred on March 29, 2008, but I reverted to the standard camera that was used to obtain the 2006 video when the high-definition camera was rendered inoperable by high humidity. A large bird that flew along the bayou and passed below was identified in the field as an Ivory-billed Woodpecker on the basis of two white stripes on the back and black leading edges and white trailing edges on the dorsal surfaces of the wings. The appearance in the video of direct and reflected (from the still surface of the bayou) images of the bird and reference objects made it possible to triangulate positions along the flight path and obtain estimates of the flight speed and wingspan. As shown in Fig. 5 and discussed in Movie S6 of Ref. 8, the bird in the 2008 video folded its wings closed during the middle of each upstroke. The two large woodpeckers are the only large birds of the region with this wing motion, which is unquestionably resolved in the video. Bret Tobalske, an ornithologist who specializes in woodpecker flight mechanics, analyzed the 2008 video using an approach that

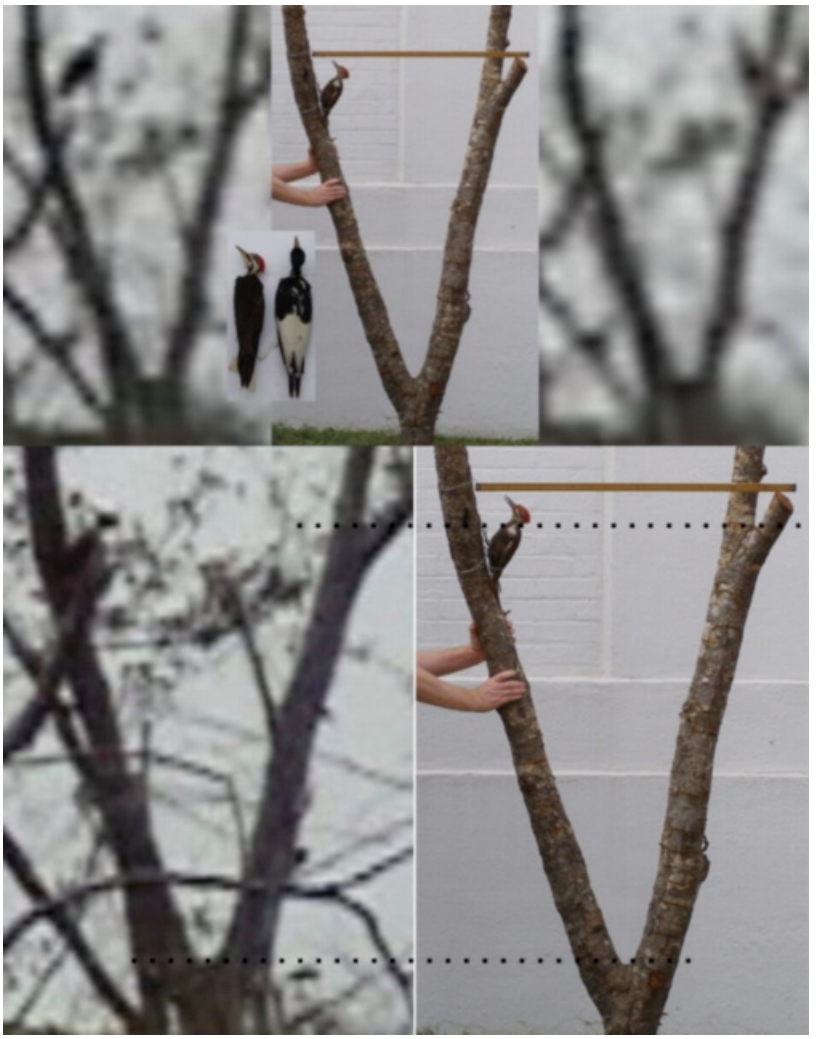

Fig. 8. A Pileated Woodpecker specimen is mounted on part of the perch tree that appears in the 2006 video.[8] Individual frames from the video are scaled using two forks in the tree specimen (dashed lines). A meter stick is placed across the location where the flight between limbs occurred. The inset shows Pileated Woodpecker and Ivory-billed Woodpecker specimens that were photographed at the National Museum of Natural History. Part of the large woodpecker in the video is hidden by vegetation in the image on the lower left, but it is in full view in the images at the top during the flight between limbs.

he had previously developed and applied to other woodpecker species.[26] Tobalske concluded that the bird in the video is a large woodpecker and provided the following assessment:[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 flap rate of the bird in the video is about ten standard deviations greater than the mean flap rate of the Pileated Woodpecker,[7] which leaves the Ivory-billed Woodpecker as the only plausible explanation. Additional characteristics of the bird in the video that are consistent with the Ivory-billed Woodpecker but not the Pileated Woodpecker are the high flight speed, narrow wings, swept-back wings, and prominent white patches on the dorsal surfaces of the wings. A former president of the Louisiana Ornithological Society, Matt Courtman, who has observed Pileated Woodpeckers on a regular basis for more than 50 years, pointed out that he has never observed that species flying up a bayou like the bird in the 2008 video.

One of the behaviors of the bird in the video was initially thought to be inconsistent with the Ivory-billed Woodpecker. Based on historical accounts of a 'duck-like' flight, it was believed that the Ivory-billed Woodpecker has a duck-like wing motion in which the wings remain extended throughout the flap cycle. In a series of paintings of the large woodpeckers in flight by Zickefoose,[27] the wings of the Pileated Woodpecker are correctly shown folding closed during the middle of the upstroke; in a proper representation of conventional wisdom at the time, the wings of the Ivory-billed Woodpecker are shown remaining extended throughout the flap cycle (duck-like flaps). I was faced with an apparent paradox during the initial inspection of the video, which revealed an unexpected wing motion. The paradox was resolved when Dalcio Dacol discovered that a photo from 1939 shows an Ivory-billed Woodpecker in flight at an instant when the wings are nearly folded closed.[7] The accounts of a duck-like flight were evidently based on the fast and direct flight rather than the wing motion. According to Dacol, the misconception about the wing motion played a role in a key decision during one of the searches that was organized after the announcement of the rediscovery of the Ivory-billed Woodpecker. A report of a sighting by one of the participants was dismissed because the observer reported that the wings were folded closed (which would be correct if it was indeed an Ivory-billed Woodpecker) rather than remaining extended throughout the flap cycle (as was mistakenly believed at the time).

The other video was obtained with a Sony HDR-HC3 high-definition video camera (mounted on kayak paddles) during an encounter with a pair of Ivory-billed Woodpeckers in Florida on January 19, 2007. The birds were repeatedly making spectacular swooping flights, and the encounter lasted more than 20 minutes. I had an excellent view through binoculars of the dorsal surface of the right wing of one of the birds, which was fully extended (and held fixed) during one of the swooping flights. The 2007 video shows several events involving flights, field marks, and other behaviors and characteristics that are consistent with the Ivory-billed Woodpecker but do not appear to be consistent with any other species of the region. A video that shows one such event would be strong evidence. A video that shows a series of such events is powerful evidence for the same reason that the series of

sightings by multiple observers in Arkansas and Florida is powerful evidence. Both scenarios may be quantified in terms of a series of events that each has a small probability; for each event in the video, there is a small probability that the bird in the event is not an Ivory-billed Woodpecker; there is a small probability that a well-prepared observer would mistakenly identify one of the common species for an Ivory-billed Woodpecker; the probability of a series of such unlikely events is the product of the probabilities of the individual events, which quickly becomes extremely small as the number of events increases.[10]

As shown in Movies S8, S9, and S10 of Ref. 8, a woodpecker in one of the events climbs upward and engages in a series of behaviors that are consistent with the Ivory-billed Woodpecker but no other species of the region, including delivering a blow that produces an audible double knock and taking off with rapid wingbeats into a flight that immediately transitions into a remarkable upward swooping flight. As shown in Movie S11 of Ref. 8, there is a takeoff into horizontal flight with deep and rapid flaps that are not consistent with the Pileated Woodpecker but are similar to the deep and rapid flaps during a takeoff of the closely related Imperial Woodpecker (*Campephilus imperialis*).[28] As shown in Movies S13, S14, S15, S16, and S17 of Ref. 8, there are upward swooping landings with long vertical ascents that are not consistent with the Pileated Woodpecker but are consistent with an account by Eckleberry. As shown in Fig. 9, a long vertical ascent allows time for maneuvering, and the bird appears to rotate about its axis during two of the ascents. In a film of the closely related Magellanic Woodpecker (*Campephilus magellanicus*),[29] there is maneuvering during a landing with a long vertical ascent. As shown in Movies S18 and S19 of Ref. 8, field marks and body proportions that are visible during and after one of the ascents are consistent with the Ivory-billed Woodpecker but no other species of the region. As shown in Movies S20 and S21 of Ref. 8, there is a downward swooping takeoff with a long horizontal glide that is consistent with an account by Audubon.

The videos provide additional information, including evidence in the form of context.[30] The first ten minutes of the 2006 video document that: (1) after a sighting, I struggled to turn the kayak around while holding the camera; (2) I used the high-pitched calls (several of which were captured in the video) to track the movements of the bird; (3) after the calls initially stopped, I backed the kayak into an observation position on the opposite bank; and (4) after hearing additional calls (but before noticing motion), I turned the camera so that the field of view was nearly centered on the perch tree. In a continuous stream of video footage, that series of events precedes the appearance of a woodpecker that appears to be larger than a Pileated Woodpecker and has several characteristics and behaviors that are not consistent with that species but are consistent with an Ivory-billed Woodpecker. Part of the context of the 2006 video is a series of six encounters in the same area during the preceding four days, which included excellent views of key field marks and hearing kent calls. The 2006 video documents an example of the role that luck can play in attempting to obtain images of the Ivory-billed Woodpecker. When perched at a distance of 128 m, the bird was lost in the clutter of vegetation. If I had managed to spot it after noticing the motion, I could have zoomed the camera and obtained better footage.

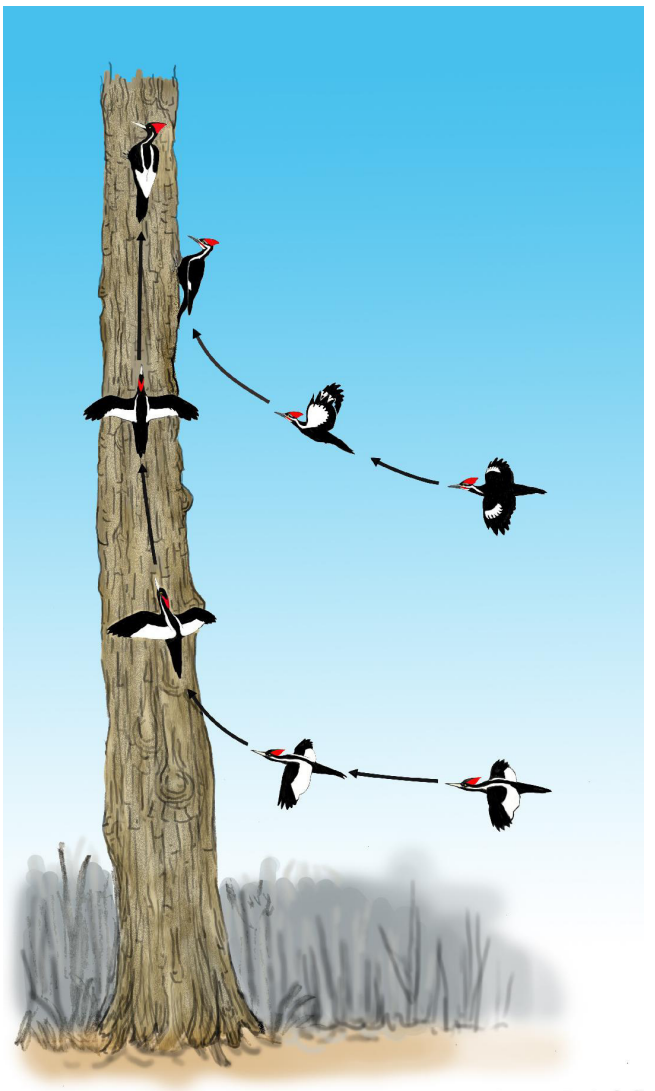

Fig. 9. Illustrations of upward swooping landings by the large woodpeckers.[10] The Pileated Woodpecker typically swoops upward a short distance before landing on a surface that faces the direction of approach. The Ivory-billed Woodpecker has long vertical ascents that allow time for maneuvering and landing on surfaces that do not face the direction of approach.

Both types of luck came into play during the encounter when the 2008 video was obtained. If the high-definition camera (which has higher resolution and allows manual focusing) had been operable that day, I might have obtained video footage that clearly shows the definitive dorsal field marks. The video documents the fact that I turned my head to the left and looked down the bayou just as the bird was coming into view. If I had been looking in another direction at that moment, the bird might have passed directly

below without being seen. In the debate that took place in *Science* and *Nature*, the strongest evidence was deemed to be less relevant than opinions such as the following:[12]

> "It's just a perfect recipe for your brain to fill in the gaps," Sibley says. "You get a brief glimpse and an impression... and your brain turns it into an ivory-billed woodpecker."

This characterization does not apply to any of my ten sightings; in the case of the flyunder, the video documents that I had an ideal vantage point for observing the definitive dorsal field marks from close range and nearly directly above and that I followed the flight of the bird for about ten seconds. The flyunder occurs more than 50 minutes into the video, which documents that I was keeping watch out over the treetops from a tree that was selected specifically for that purpose by Steve Sillett, a distinguished tree climbing biologist whose work has been featured in *National Geographic*[31,32] and *The Wild Trees*.[33]

The 2007 video was obtained at a site where Hill and his colleagues had recently had a series of sightings. I was working with Hill's team to follow up on an encounter late the previous afternoon with two Ivory-billed Woodpeckers that were observed flying away. I made what turned out to be a lucky guess that they had flown in the direction of a nest or roost after being flushed. The next morning, I followed a path that flanked around the area and came upon the birds. The video documents my efforts to (1) keep the kayak in position just behind debris that prevented me from paddling closer to the birds that appear in the video; and (2) place the paddle-cam on the ground and leave it aimed in the direction of the birds during a brief period when I got out of the kayak. The audio track captured dialogue with a member of Hill's search team, who arrived on the scene during the encounter and was present during some of the events that appear in the video. After mentioning that there were two birds making swooping flights and that I saw the white trailing edge on one of the wings, I told the other searcher that we should report the sighting to the others by radio.

2.5. *Decades of Folly and Politics*

Cold fusion was a fiasco because scientists made mistakes. Scientists who reported sightings of the Ivory-billed Woodpecker were not mistaken, but the issue became a fiasco for reasons discussed here. When an endangered species nears extinction, an aggressive conservation program that is based on the needs of the species may be the only hope for saving it. If not for the establishment decades ago of such programs for the California Condor (*Gymnogyps californianus*), Whooping Crane (*Grus americana*), and Kirtland's Warbler (*Setophaga kirtlandii*), those species might be extinct by now. There has never existed a sustained conservation program for the Ivory-billed Woodpecker, which has been the victim of decades of folly and politics. After this species was feared extinct for the first time, a pair was discovered in Florida in 1924,[3] but those birds were shot by a taxidermist the next day. After it was again feared extinct, the last known nests were discovered in the 1930s. The initial report was dismissed, however, until proof was obtained by shooting one of the few remaining Ivory-billed Woodpeckers. Those birds disappeared as the Singer Tract was

being logged. Even though a history of elusiveness had already been established by the 1930s, many reports of sightings were dismissed during the decades that followed.

When John Dennis reported a sighting in Texas in 1966,[17] he should have been taken seriously on the basis of having previously discovered and photographed Ivory-billed Woodpeckers in Cuba,[15] but James Tanner said, "Dennis badly wants to find ivorybills; when he says he has seen them he believes he has seen them — but he hasn't."[34] At the time, Tanner was "generally recognized as the country's leading authority" on the Ivory-billed Woodpecker,[34] even though his study was limited to a small number of birds at one location. Dennis reported observing an Ivory-billed Woodpecker flush from the ground, which would be "very unusual for an ivorybill, very unusual," according to Tanner.[35] After listening to a recording of apparent kent calls that Dennis obtained, Tanner asked what an Ivory-billed Woodpecker would be doing in the same habitat with a Pine Warbler (*Setaphaga pinus*),[36] which can be heard singing in the recording. The flaws in those criticisms are apparent from Plate 11 of Ref. 3; the photo shows a male Ivory-billed Woodpecker perched on a tree in a pine forest, which is ideal habitat for the Pine Warbler; the caption states that a female Ivory-billed Woodpecker was on the ground at the time. It is surprising that Tanner failed to notice the connection between that photo, which appears in the most significant article on the Ivory-billed Woodpecker that was published during the 20th Century, and criticisms with which he managed to discredit Dennis. It appears that nobody else noticed those mistakes until decades later.

Tanner's views are still widely regarded as authoritative, but questions have been raised about his work. In 1939, he concluded that approximately 22 Ivory-billed Woodpeckers remained on the basis of eight months of searching and gathering information throughout the range of this species.[4] Geoff Hill stated a reluctance to criticize Tanner, which he compared to "criticizing a patron saint," but he described Tanner's attempt to estimate the population of the Ivory-billed Woodpecker as "one of the greatest follies in the history of U.S. bird conservation."[2] Richard Pough was "the foremost land preservationist of his time and a versatile innovator in bird conservation."[37] During the winter of 1943–44, he spent several weeks conducting a survey and observing the last known Ivory-billed Woodpecker in the Singer Tract,[38] where Tanner had recently carried out his study. Pough pointed out that Tanner's report does not begin to "explain the reasons for the drastic decline in this species" and still left "a lot of questions concerning the ivorybill unsolved." He explained that a drought in the 1920s caused a die-off of mostly mature trees that made the habitat favorable for Ivory-billed Woodpeckers in the early 1930s. Pough brought into question Tanner's assertion that the Ivory-billed Woodpecker requires virgin forest, noting that, in a limited study at one location, Tanner "found only one nesting pair and their young" and "actually saw and studied only one other bird." On the basis of the history of the region and the presence of old cottonwoods, Pough made a case that the Singer Tract was not a virgin forest. Tanner's unfounded claim about the need for virgin forest has undermined conservation by (1) fostering a mindset that there is no hope for saving the Ivory-billed Woodpecker from extinction (since very little such habitat remains within its range) and (2) serving as a basis for dismissing reports of sightings in areas that lack such habitat.

Since the contributions of John Fitzpatrick and Geoff Hill and their colleagues were not sufficient to bring an end to decades of folly and politics, it seems that this issue could benefit from the influence of scientists outside the field of ornithology. The debate that took place in *Science* and *Nature* was an opportunity for such influence to come into play. Shortly after obtaining the 2006 video, I informed the editor of *Science* of a series of sightings in Louisiana and new evidence that is stronger than the evidence presented in the original paper. When an issue becomes controversial, new findings that either support or refute the original findings are usually welcomed wholeheartedly. In this case, the new findings included stronger evidence, observations of a different type (a series of sightings by one observer), a report of a pair of Ivory-billed Woodpeckers (not just one bird), and observations that occurred in a different state (about 500 km from the Big Woods). Nobody in Arkansas had a series of encounters comparable to my seven encounters in five days (five sightings with definitive field marks and flights observed at close range; kent calls heard on two occasions, once coming from two directions at the same time). According to an avian artist whose depiction of an Ivory-billed Woodpecker had been featured on the cover of the *Auk* the previous month, the large woodpecker appearing in the video has characteristics and behaviors that are consistent with the Ivory-billed Woodpecker but not the Pileated Woodpecker. None of the evidence from Arkansas received a comparable assessment from an independent expert. A few months earlier, *Science* (23 December 2005, p. 1885) had singled out the Ivory-billed Woodpecker as one of the "Areas to Watch in 2006." It was a pivotal moment when the controversy was escalating, but the editor dismissed the only new evidence that anyone had managed to obtain, apparently without giving it any serious consideration.

The strongest evidence might have made a difference in the debate on the persistence of the Ivory-billed Woodpecker, but the publication of this information was delayed for a decade for reasons that had nothing to do with science. When this body of evidence was finally published,[8] John Fitzpatrick sent me a note of congratulations for "perseverance against long odds and irrational opposition." After receiving undeserved criticism for leading the search in Arkansas and having the courage to publish the results, Fitzpatrick said, "Nobody else had the balls to do it."[12] During the struggle to publish my findings, I realized that such courage is rare when it comes to the Ivory-billed Woodpecker. I made more than 40 submissions before finding an editor who was willing to disregard politics and evaluate a comprehensive report of my findings on the basis of logical reasoning. A by-product of all those submissions is a collection of comments by anonymous reviewers[10] that helps to reveal the depth of the folly and politics that have been undermining the conservation of the Ivory-billed Woodpecker for several decades.

A recurring theme in the reviews was Carl Sagan's quote, "extraordinary claims require extraordinary evidence." It is amazing that the Ivory-billed Woodpecker has defied the odds and managed to survive despite decades of neglect, but there is nothing extraordinary about the rediscovery of a species that already had a history of multiple rediscoveries and remarkable elusiveness (a history that is easy to understand in terms of an outlying combination of factors related to habitat and behavior). There is no logical reason to require

extraordinary evidence to demonstrate the persistence of the Ivory-billed Woodpecker. It is sufficient to obtain video footage that shows characteristics consistent with that species but no other species and for those characteristics to be sufficient in number to rule out the plausibility of any other explanation. Such evidence is contained in the videos that were excluded from the debate that took place in *Science* and *Nature*. Although extraordinary evidence is not required, the videos are extraordinary in the sense that: (1) they contain the strongest evidence that has been obtained during the past several decades; and (2) they show several types of flight and other behaviors that do not appear in the 1935 film.

According to some reviewers, a convincing case that the Ivory-billed Woodpecker is extinct was made by analyzing the record of sightings.[39–42] A precondition for such studies is to dismiss all reports in recent decades, including numerous reports by well-prepared observers and three that are supported by video evidence that nobody has been able to refute. It might be possible to estimate the extinction date of a species from a record of sightings that is adequately sampled throughout the range of the species, but the record of sightings of the Ivory-billed Woodpecker is extremely sparse both spatially and temporally, and there have been large variations in the intensity of efforts to find these birds with the comings and goings of searchers such as Arthur Allen, John Dennis, John Fitzpatrick, Geoff Hill, and others. It seems doubtful that reliable information can be extracted from such a sparsely and irregularly sampled data set, but those studies "point to the inescapable conclusion that the Ivory-billed Woodpecker is now extinct," according to the authors of one of them.[41] On one side of the debate, there have been various duplicative attempts to make a case that the Ivory-billed Woodpecker is extinct by gleaning information from a dubious source. On the other side of the debate, the evidence for the persistence of the Ivory-billed Woodpecker includes: (1) numerous reports of sightings by well-prepared observers (including an ornithologist) in Arkansas and Florida; (2) a report of ten sightings by a well-prepared observer in Louisiana and Florida; and (3) video footage obtained during three of the encounters in Louisiana and Florida that shows birds with flights, field marks, and other behaviors and characteristics that are consistent with the Ivory-billed Woodpecker but no other species of the region.

The analysis of the 2008 video is based on using flap rate to rule out the Pileated Woodpecker. Some reviewers claimed that flap rate decreases as size increases and that the Ivory-billed Woodpecker should therefore have a lower flap rate than the Pileated Woodpecker, but flap rate depends on multiple parameters. Pennycuick applied a data set for a wide range of species to develop a three-parameter model for flap rate.[43,44] According to this empirical model, high body mass correlates with high flap rate, which is the opposite of the dependence claimed by reviewers. The other parameters are the wingspan and the surface area of the wings. There is a relatively small difference between the wingspans of the two large woodpeckers, but the Ivory-billed Woodpecker has narrower wings, which correlates with a high flap rate. The model predicts that the Ivory-billed Woodpecker has a higher flap rate than the Pileated Woodpecker, which is consistent with Tanner's account of rapid wingbeats. The Imperial Woodpecker (which may be extinct) is the largest woodpecker in the world and a close relative of the Ivory-billed Woodpecker. There were no further

claims that the Ivory-billed Woodpecker should have a lower flap rate than the Pileated Woodpecker following the publication of a long-lost film,[28] which revealed that the even larger Imperial Woodpecker also has rapid wingbeats.

Reviewers also questioned the 15.2 m/s flight speed of the large woodpecker in the 2008 video, which is substantially above the range of 7.5 to 11.6 m/s that Tobalske obtained for the Pileated Woodpecker.[26] There were claims that the high flight speed could have been affected by a tail wind, but the video shows delicate strands of Spanish moss hanging motionless on a morning that was still (as can be verified from weather archives). A reviewer of a submission to *BMC Ecology* in 2011 tried to bring into question Tobalske's flight speed data for the Pileated Woodpecker by claiming that (1) larger birds have greater flight speeds than smaller birds, but there are several examples of the opposite dependence (by a large margin in some cases) in the data set obtained by Pennycuick;[43] and (2) estimates of flight speed obtained in the field are "absurd or bogus," but it is straightforward to obtain reliable estimates of flight speed using landmarks.[26] According to the same reviewer, reporting the analysis and conclusions of an expert on woodpecker flight mechanics was an "appeal to authority," but there has been no input from an independent expert on any of the evidence for the persistence of the Ivory-billed Woodpecker that is more relevant and significant than Tobalske's input on the 2008 video. According to a model that is based on the physics of vortex shedding,[45,46] the flap rate is proportional to the flight speed, with a proportionality factor that depends on the wingspan. For a pair of species with approximately the same wingspan (as is the case for the two large woodpeckers), the model predicts that, if either the flight speed or the flap rate is substantially greater for one of the species, the other quantity will also be greater for that species. There is mutual consistency among the following: (1) the vortex shedding flap rate model; (2) historical accounts that the Ivory-billed Woodpecker has a high flight speed and rapid wingbeats; and (3) the fact that the bird in the 2008 video, which was identified in the field as an Ivory-billed Woodpecker, has a high flight speed and rapid wingbeats.

A reviewer of a submission to the *Proceedings of the National Academy of Sciences* in 2009 made the following claims: (1) "A sample size of one flight from one bird is not conclusive," but it is indeed possible to rule out the Pileated Woodpecker in a single flight on the basis of the known flap rate statistics of that species; (2) the prominent white patches on the dorsal surfaces of the wings "could potentially derive from solar specular reflection," but the video reveals that the sky was overcast that morning (as can be verified from weather archives); and (3) "The low temporal resolution of the camera precludes detailed assessment of wingbeat motions," but Tobalske had no problem digitizing the wingtip motion from the NTSC video, which is sampled at 60 frames per second and clearly reveals the motions of the wings. The same reviewer made the following comments:

> The estimates of wingbeat frequency suggest values much higher than those known to characterize flight of Pileated Woodpeckers, but the inference that the sequence is therefore necessarily that of an Ivory-billed Woodpecker (for which no frequency data are available in any event) is flawed. The larger size of the latter species should

> correspond to lower and not higher wingbeat frequencies given the well-characterized negative allometry of this quantity in birds and other flying animals. In fact, an alternative explanation is simply that the time base is incorrect, i.e., that the sequence corresponds to 30 frames/second rather than 60 frames/second, thus yielding a wingbeat frequency for the sequence that is closer to 3.5 Hz and well within the range for a Pileated Woodpecker. If this is the case, then the flight speed estimate is also too high by a factor of two, which would bring the value to 7.5 m/s which is more realistically consistent with reported flight speeds for a Pileated Woodpecker.

These comments reflect a lack of awareness of Pennycuick's findings and Tanner's account of rapid wingbeats. By speculating that the temporal sampling had been altered, the reviewer essentially conceded that the large woodpecker in the video cannot be a Pileated Woodpecker. That line of discussion could be interpreted as an implication of fraud, but I was not given an opportunity to provide the original digital videotape for inspection. It would be easy for anyone to verify the flap rate from the raw digital video.[25] By doing some fact checking, the editor could have confirmed that the temporal sampling was correct and pointed this out to a reviewer who was unable to refute the evidence through logical reasoning. This submission to one of the leading science journals was another missed opportunity for influence from outside the ornithology community to have a positive impact. Some of the critics have been more direct in suggesting fraud. Speculations that the large woodpecker in the 2006 video is a different *Campephilus* woodpecker that was filmed in South America were debunked by launching a drone from the spot where the video was obtained.[47] Trees that appear in the 2006 video were still recognizable 15 years later. The rocket towers at Stennis Space Center and other landmarks came into view as the drone gained altitude. The same approach was used to show that the 2008 video was obtained a short distance up the same bayou.

Tobalske's paper on woodpecker flight mechanics[26] is a tour de force of field work, laboratory work, data analysis, and innovation. None of the reviewers attempted to bring into question Tobalske's conclusion that the bird in the 2008 video is a large woodpecker. They instead put forth easily refutable claims such as the following: the Ivory-billed Woodpecker should have a lower flap rate than the Pileated Woodpecker; the high flight speed could be due to a tail wind; larger birds have higher flight speeds than smaller birds; estimates of flight speed obtained in the field are bogus; the prominent white patches on the dorsal surfaces of the wings could be due to solar specular reflection; the temporal sampling of the video is not sufficient for analyzing wing motion; nothing can be concluded from a single event; and the speed of the video was off by a factor of two. Whether or not the wings are folded closed is a yes/no question, and there is no question that the wings are folded closed in the middle of the upstroke. Only two large birds of the region have that wing motion in cruising flight. Tobalske digitized the wing motion, applied an analysis that he had previously developed and applied to other woodpeckers, and concluded that the bird in the video is a large woodpecker. It follows from Tobalske's conclusion and the flap rate

that the Ivory-billed Woodpecker is the only plausible explanation; several characteristics of the bird in the video are consistent with that species but not the Pileated Woodpecker.

In recommending publication, two reviewers of a submission to *PLOS ONE* in 2013 provided the following sets of comments:

> This is a fascinating paper, laying a claim of a highly controversial topic, namely, the flight characteristics of the Ivory-billed woodpecker, actually, the very continuing existence of it. The work is indirect but the effort is highly methodical and justifiable. It will surely create disagreement but I strongly recommend the paper for publication so that there is a framework to foster open discussion and debate.

> The manuscript contains an insightful analysis of flight characteristics of the Ivory-billed and Imperial woodpeckers, using analysis of historical and video data to make a case for considering the footage in the putative videos to be that of the Ivory-billed woodpecker. Flight characteristics are the key to the analysis, although other aspects of wing shape and markings are also pointed out. Looking at the putative video before seeing the analysis, one may wonder how any progress on deciding if the video is of the Ivory-billed woodpecker can be made, since it is fleeting footage from far away. I am impressed by the author's being able to provide an analysis of flap rate and takeoff and landing characteristics that is very compelling.

The other reviewer made the following claims: (1) "The poor quality of the data does not allow proper kinematic analysis," but an expert on woodpecker flight mechanics had no problem analyzing the video, which unquestionably shows the wings folding closed in the middle of each upstroke; and (2) "The strange attempt to use a kinematic model shows the ignorance of the author," but it would be straightforward for any scientist to apply that model,[45,46] which is based on a simple equation involving the flap rate, flight speed, and wingspan. The reviewer did not provide any details to support the claim that the model was used improperly, but I consulted with one of the developers of the model, Adrian Thomas of Oxford University, who confirmed that I applied it properly for a previous submission. When asked why the positive reviews were dismissed and the submission was rejected on the basis of a negative review that contains no valid criticisms, the editor responded with the following:

> For your information, there is a long list of potential reviewers for this ms who have all declined, including all the ones you have suggested. The reasons they gave for declining have also contributed to my decision, which was reached in consultation with the editors.

The editor admitted that the decision was influenced by "potential reviewers" who did not actually review the paper. There was no indication that the decision was based on the evidence and its analysis or any type of logical reasoning.

Some of the comments by anonymous reviewers seem to suggest something other than a mere lack of awareness of facts. A reviewer of a submission to *MDPI Biology* in 2016 made the following comments:

> We have what is called the 'scientific method' for a reason. Nearly 500 years ago science existed in an age when men of wealth and power made declarations of what is true and what isn't true in science — and progress and understanding in science was abysmal. The development of the scientific method gave science a yardstick by which to measure whether something was true or not — whether something existed or not. Scientific credibility — not wealth or power — is the foundation on which decisions to expend vast sums of public resources. Of course wealth and power still give sway to some major expenditures — such as in the case of the ivory-billed woodpecker, but science gives us the tool to call them on it.

The reviewer pontificated about the scientific method but did not specifically address the evidence and its analysis, which is based on the scientific method (e.g., the analysis of the 2008 video is based on woodpecker flight mechanics and the statistics of avian flap rate). A reviewer of a submission to *Frontiers in Zoology* in 2010 made the following comments:

> I know as a result of discussions with others, including members of the Ivory-billed Woodpecker Recovery Team and others associated with the searches of recent years, that the videos mentioned at the beginning of the results section and presented with this manuscript have been thoroughly analyzed by members of the Ivory-billed Woodpecker Recovery Team and convincingly dismissed as being videos of a pileated woodpecker, red-headed woodpecker, and possibly a third species — but almost certainly not one of the images is of an ivory-billed woodpecker.

Without specifically addressing the evidence and its analysis, the reviewer claimed that unspecified individuals had "thoroughly analyzed" and "convincingly dismissed" the videos. Another reviewer of the same submission (who disclosed his identity in the review) was a member of the group that had supposedly "convincingly dismissed" the videos. He recommended publication and provided the comment, "After a rather intensive and careful review of the evidence provided by the author, I am inclined to agree that this manuscript offers relatively strong evidence of at least one observation of ivorybill in 2008."

3. Vocalizations, Double Knocks, and Acoustic Detections

During a study near the last known nests in the 1930s, kent calls were recorded and other types of calls were observed. Tanner described a high-pitched call that is given when an Ivory-billed Woodpecker is alarmed.[4] I heard high-pitched calls coming from the direction of an alarmed Ivory-billed Woodpecker on two occasions, and I recorded several of them during the second encounter. Allen and Kellogg reported a scolding call,[3] which may be what I heard just before the high-pitched calls started on February 18, 2006. In 1968, John

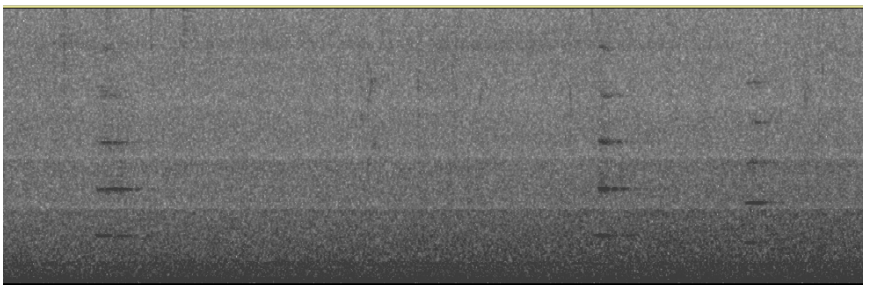

Fig. 10. Spectrograms of three putative kent calls that were recorded on March 16, 2006, in the Choctawhatchee River swamp.[6] As for all known and putative calls of the Ivory-billed Woodpecker, these calls consist of harmonics that are excited simultaneously in time. The horizontal axis spans 10 s. The vertical axis spans 0 to 5 kHz.

Fig. 11. Spectrograms of five of the putative alarm calls that were recorded on February 20, 2006, in the Pearl River swamp. The harmonics of these high-pitched calls are at 2.35 and 4.70 kHz. The fundamental frequency of 2.35 kHz is more than double the fundamental frequency for each of the putative kent calls in Fig. 10. The horizontal axis spans 30 s. The vertical axis spans 0 to 5 kHz.

Dennis obtained an audio recording of apparent kent calls in an area where he previously had a sighting. Appearing in Fig. 10 are spectrograms of three putative kent calls from an audio recording that was obtained in the Choctawhatchee River swamp on March 16, 2006; that recording may be downloaded from Appendix 10 of Ref. 6. Appearing in Fig. 11 are spectrograms of five of the putative alarm calls that I recorded in the Pearl River swamp on February 20, 2006. As for all other known and putative calls of the Ivory-billed Woodpecker, the spectrograms in Figs. 10 and 11 consist of simultaneously excited harmonics. In contrast, the spectrogram of the song of a Wood Thrush (*Hylocichla mustelina*) in Fig. 12 has a more complex structure. The fundamental frequency of 2.35 kHz of the high-pitched calls in Fig. 11 is more than double the fundamental frequency of the putative kent calls in Fig. 10. If the high-pitched alarm calls that Tanner reported have the same type of harmonic structure as the kent calls, the sonograms appearing in Fig. 11 are consistent with what would be expected. The high-pitched calls sound somewhat similar to the Blue Jay (*Cyanocitta cristata*) bell call,[48] but published examples of those calls do not have the simple structure of the high-pitched calls (simultaneously excited harmonics). The Blue Jay is a conspicuous bird that usually makes its presence known with 'jay' calls, but there are no such calls in a

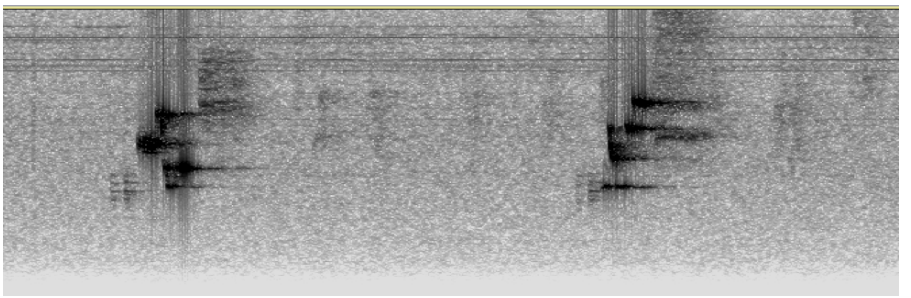

Fig. 12. Spectrograms of the song of a Wood Thrush, which does not have the simple harmonic structure of the calls in Figs. 10 and 11. The horizontal axis spans 10 s. The vertical axis spans 0 to 5 kHz.

continuous stream of more than 35 minutes of video footage that was obtained during the encounter.

The Ivory-billed Woodpecker and other *Campephilus* woodpeckers signal with double and multiple knocks rather than with the drumming that is typical of other woodpeckers. There are no double knocks in the audio recording from 1935, but audio recordings of several putative double knocks from the Choctawhatchee River swamp may be downloaded from the Appendices of Ref. 6, and there exist many recordings of the double and multiple knocks of other *Campephilus* woodpeckers. An apparent double knock was captured in the 2008 video shortly before an Ivory-billed Woodpecker appeared flying up the bayou.[7] During one of the events in the 2007 video, a woodpecker climbs upward and engages in several behaviors that are consistent with the Ivory-billed Woodpecker but no other woodpecker of the region; after moving to the right and then to the left, the bird is visible delivering a blow that is accompanied by an audible double knock (with a slight delay due to the distance to the bird). When studying that footage, I was faced with another apparent paradox: there appears to be only one thrust of the body, but there are two audible knocks. I resolved the apparent paradox while studying video footage of a drumming Pileated Woodpecker. I noticed that the drumming is driven by motions of the body. When the motions stop (i.e., the driving force is turned off), there are a few additional impacts of the bill. This observation led to the idea that drumming and double knocks may be modeled as a mechanical system in which an object experiences a restoring force when it is displaced from an equilibrium point. The object may have periodic or transient motions, depending on how it is forced.

We consider the following harmonic oscillator model of a drumming woodpecker:[9]

$$\frac{d^2x}{dt^2} + p\frac{dx}{dt} + qx = R(t), \tag{4}$$

where x is the displacement, t is time, the coefficient p is related to damping, the coefficient q is related to the natural frequency of the system, and $R(t)$ is the forcing function. 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 with a loss of energy after each impact. Drumming is driven by periodic

oscillations of the body that are tuned to the natural frequency range of the system. When the bill impacts the wood at $x = x_0$, it rebounds with a loss of energy that may be modeled with the change in velocity,

$$\frac{dx}{dt} \to -\alpha \frac{dx}{dt}, \tag{5}$$

where $\alpha < 1$. In order to illustrate basic behaviors, we consider the case $p = 0.2$, $q = 0.3$, $\alpha = 0.8$, and $x_0 = 0.2$, with the periodic forcing function,

$$R(t) = \begin{cases} \sin(t) & 2\pi < t < 20\pi \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

and the impulsive forcing function,

$$R(t) = \exp[-(t - 20\pi)^2]. \tag{7}$$

Solutions for these cases appear in Fig. 13. For the periodic case, there are a few additional impacts after the driving force is turned off, which are related to the double or multiple knocks that result from an impulsive driving force. In the supplemental material of Ref. 9, there is a video of a Pale-billed Woodpecker (*Campephilus guatemalensis*) giving a double knock that is driven by a single thrust of the body. The supplemental material of Ref. 9 also includes audio recordings of the double and multiple knocks of several *Campephilus* woodpeckers.

There are similarities between searching for Ivory-billed Woodpeckers and searching for submerged objects in the ocean. In both cases, the objects may be extremely difficult to find, but they may produce sounds that allow them to be detected and located. When an Ivory-billed Woodpecker is flying above the treetops, it is like a submarine that may be relatively easy to detect after surfacing. This was the motivation for the approach of keeping watch from tall trees that provide clear views over the surrounding forest. This approach was used to obtain the 2008 video, although it ended up working in an unexpected way. When an Ivory-billed Woodpecker remains below the treetops, it is like a submarine that is hidden in a vast ocean of vegetation. Autonomous cameras and audio recorders were used during the searches in Arkansas and Florida. A camera provides coverage of only a minuscule fraction of a forest; this approach is somewhat analogous to placing a camera in the ocean and hoping that a submarine passes in front of it at close range. Numerous recordings of kents and double knocks were obtained in Arkansas and Florida with recording stations that each consisted of a single microphone. Such recordings are useful when trying to determine if Ivory-billed Woodpeckers might be present in an area, but they are not deemed to be conclusive evidence for persistence because similar sounds are known to originate from sources other than an Ivory-billed Woodpecker. By going a step further and using a horizontal array of microphones at each recording station, it would be possible to detect weaker sounds and determine the directions of sources by beamforming. There might be an advantage to deploying such an array above the treetops, where long-range transmission of sounds might be more favorable than transmission through the thick

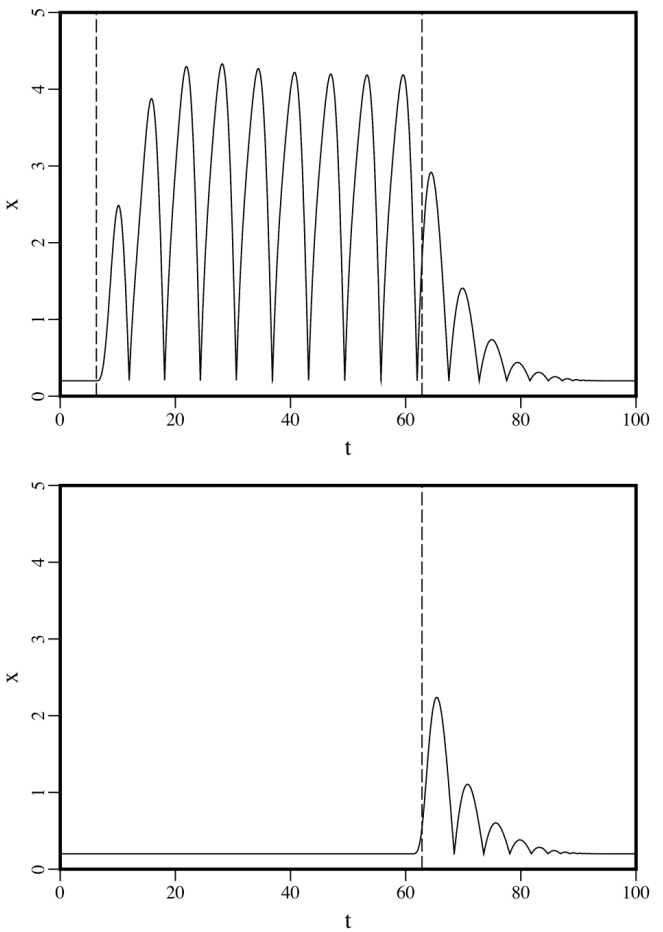

Fig. 13. Solutions of Eq. (1) corresponding to periodic (top) and impulsive (bottom) forcing.[9] The vertical dashed lines indicate the points at which the periodic driving force is turned on and off and when the impulsive driving force reaches its maximum amplitude.

vegetation in the forest. With such a system, it might be possible to track the movements of an Ivory-billed Woodpecker and locate a nest. One of the advantages of acoustic systems is that they are less invasive than human searchers, which may drive a wary bird out of an area; it was my impression that this happened during the searches in Louisiana and Florida after participating in them.

4. Discussion

Audio recordings that were obtained in the Singer Tract in 1935 contain kent calls but none of the other vocalizations or double knocks of the Ivory-billed Woodpecker. Recordings of apparent kent calls were obtained by John Dennis in 1968 and during the searches in Arkansas and Florida. Recordings of apparent double knocks were obtained in Arkansas, Florida, and Louisiana. All known and putative vocalizations of the Ivory-billed Woodpecker

consist of simultaneously excited harmonics, including high-pitched calls that were recorded in Louisiana, which were heard coming from the direction of an alarmed Ivory-billed Woodpecker on two occasions. Having a fundamental frequency that is more than double the fundamental frequency of kent calls, the high-pitched calls are consistent with high-pitched alarm calls that Tanner described. A harmonic oscillator model was used to relate the double knocks of the Ivory-billed Woodpecker to the drumming that is typical of most woodpeckers. According to this model, a single thrust of the body is sufficient to produce two blows with the bill in rapid succession, which is consistent with a double knock event in the 2007 video and footage of other *Campephilus* woodpeckers giving double knocks. Although recording systems based on single microphones were successful during the searches in Arkansas and Florida, audio recordings of kent calls and double knocks are not sufficient to confirm persistence. Going a step further and using horizontal arrays of microphones (perhaps deployed above the treetops) has the potential to detect weaker (and/or more distant) sounds, determine the directions of sources, and ultimately lead to the discovery of a nest.

Prior to the discovery of a film from 1956, there did not exist any known images of a living Imperial Woodpecker, which may now be extinct. That film provided information about the Imperial Woodpecker that was thought to have been lost forever. The videos that were obtained in Louisiana and Florida provide information about the Ivory-billed Woodpecker that was thought to have been lost forever. No flights appear in the film that was obtained in 1935, but the videos show several types of flight and other behaviors that are consistent with historical accounts. The evidence for the persistence of the Ivory-billed Woodpecker includes: (1) sightings by several well-prepared observers in Arkansas and Florida; (2) ten sightings by a well-prepared observer in Louisiana and Florida; and (3) three videos obtained in Louisiana and Florida that show flights, field marks, and other behaviors and characteristics that are consistent with the Ivory-billed Woodpecker but no other species of the region. This body of evidence should have been sufficient to resolve the issue when it was being debated in *Science* and *Nature*, but the strongest evidence was inexplicably excluded. Those journals could have fostered an open debate by including all of the relevant information, but they instead published biased reports that caused the issue to become marginalized and helped set back the conservation of the Ivory-billed Woodpecker by more than a decade. There is a need to set folly and politics aside and establish an active conservation program for the Ivory-billed Woodpecker, while there may still be time to save this magnificent bird from extinction.

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