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METHOD

Sounding out the nest: Unobtrusive localisation of North Island brown kiwi (*Apteryx mantelli*) incubation burrows

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Abstract: Monitoring breeding outcomes of cryptic nocturnal species such as the North Island brown kiwi (*Apteryx mantelli*) is an important aim for conservation management in New Zealand. While fitting male kiwi with radio transmitters enables incubation burrows to be found and monitored, it is invasive and expensive. Remote monitoring methods (without handling of birds) are preferable. Here we investigate the extent to which it is practical to find North Island brown kiwi incubation burrows based on remote monitoring, motivated by anecdotal reports that incubating males call close to their incubation burrow on first emergence. We test this observation, and then use it to demonstrate how a combination of acoustic recorders, human listening, and trail cameras can be deployed to locate the burrow with minimal disturbance, based on the male's first call of the night. Our analysis of an incubating brown kiwi male's first call in the evening as a function of distance from the burrow shows that for more than half the time monitored he called within 10 minutes of leaving his burrow and that on these nights, he was usually less than 35 m from it. Along with backtracking of kiwi footsteps, this enables the localisation of the burrow. We outline a workflow for the method based on our experience and discuss how it can be made more efficient and usable in the future. Our method facilitates the finding of nests, and hence of chicks, without the need for adult kiwi to be fitted with transmitters.

Keywords: acoustic, incubation, localisation, monitoring, North Island brown kiwi

Introduction

The monitoring of endangered bird populations is a crucial part of conservation management, for reasons as diverse as detecting changes in population density, checking individual health, and tracking breeding and fledging success. For species such as North Island brown kiwi (*Apteryx mantelli*), which are nocturnal, visually cryptic and typically maintain large territories (McLennan et al. 1987; Taborsky & Taborsky 1992), monitoring is often based on telemetry; radio transmitters are attached to the bird (mounted on the leg in the case of kiwi; Miles & McLennan 1997; Colbourne et al. 2020), allowing the locations of individuals to be identified. Individual birds are recruited into a study by being caught, either in their day shelters using trained dogs, or at night using playback or whistling to entice birds towards human catchers (Robertson & Colbourne 2017).

For kiwi it is particularly important to monitor breeding success, since in most kiwi species the adults are relatively safe from predation by mustelids, but the chicks and juveniles are not (McLennan et al. 2004). The threat of kiwi chick predation has resulted in a widely used captive rearing programme based on eggs recovered from incubation burrows (Operation Nest Egg, ONE) (Colbourne et al. 2020). Therefore, even when the adult kiwi population is relatively stable, many male kiwi have radio transmitters attached solely to enable the following of the chicks that they may or may not rear in any given year; in the North Island brown kiwi the male is responsible for incubation (Taborsky & Taborsky 1991).

While radio telemetry is considered the gold standard for monitoring kiwi, there are several concerns with the use of transmitters, primarily potential welfare issues for the birds and resource and cost implications for those monitoring them. For the first point, although there are no publicly available data for kiwi, there are anecdotal reports of birds being caught in climbing vines by their transmitter. A meta-study of outcomes for birds with and without transmitters/data loggers found negative impacts of the devices for birds (Barron et al. 2010), although none of the research included leg-mounted transmitters. Regarding research and financial costs, experienced kiwi practitioners are needed to fit the transmitters, and human distance trackers with telemetry equipment to monitor the birds. Due to battery limitations, transmitters need to be replaced annually, which as well as requiring handling of these wild animals, has a significant cost: currently, an adult kiwi transmitter costs c. NZ$500.

Alternative methods of remotely monitoring kiwi populations include motion-triggered camera traps and acoustic

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monitoring. While cameras can be used to monitor a known burrow, positioning of the camera is critical if the chicks are to be seen, requiring knowledge of the burrow location. Further, the chick leaves the burrow at around 10 days old, after which it is unlikely to be caught on camera. For acoustic recorders the main difficulty is that young kiwi do not call (Colbourne & Kleinpaste 1984; Corfield et al. 2008). Thus, relying solely on remote methods to monitor a population risks missing factors such as invasion by mammalian predators that can be detrimental to the recruitment rate.

Adult kiwi call intermittently while active (typically between dusk and dawn). Although the calls are sexually dimorphic, it is not currently possible to differentiate between calls for pair contact, territory defence, or mate seeking (Corfield et al. 2008; Digby et al. 2013). However, several groups monitoring kiwi have anecdotally reported that male kiwi call soon after leaving the incubation burrow, possibly to alert the female.

In this paper we evaluate the use of these calls to locate the incubation burrow, based only on acoustic recorders and manual listening, coupled with some trail cameras late in the analysis. The motivation is to find chicks without the need to maintain transmitters on the adults. These chicks could then be monitored using transmitters, as appropriate. We conclude by suggesting methods to streamline and partially automate the procedure.

Geographic Setting

Our study area is part of the Remutaka ranges adjacent to the township of Wainuiomata (41.2624° S 174.9469° E; Fig. 1). While kiwi were historically not recorded in the area, little spotted kiwi (*Apteryx owenii*) and/or Rowi (*Apteryx rowi*) were most likely present in prehistoric times, and are presumed to have died out during human settlement (Davidson 1978). In 2006, the Remutaka Conservation Trust (RCT, then called the Rimutaka Forest Park Trust), a group of community volunteers, introduced the first North Island brown kiwi to the Forest Park. The first release of eight birds from captive facilities was supplemented by occasional further releases of kiwi house birds and followed three years later by the release of a further 20 birds that were translocated from Little Barrier Island / Te Hauturu-o-Toi (Hauturu) in the Hauraki Gulf.

For the first 5 years the kiwi were tracked extensively by RCT volunteers using radio transmitters on males, females and chicks. Once the population exceeded 50 birds, radio transmitters were gradually removed, with only a small core group of 10 breeding male kiwi retained in the monitoring programme. In 2018 it was decided to recapture some males to more accurately gauge the effects that several mast years and an improved trapping regime had had on population growth. Therefore, the decision was made to undertake this study to establish a remote detection method for identifying incubation nests, as a supplement to night catching and the use of dogs.

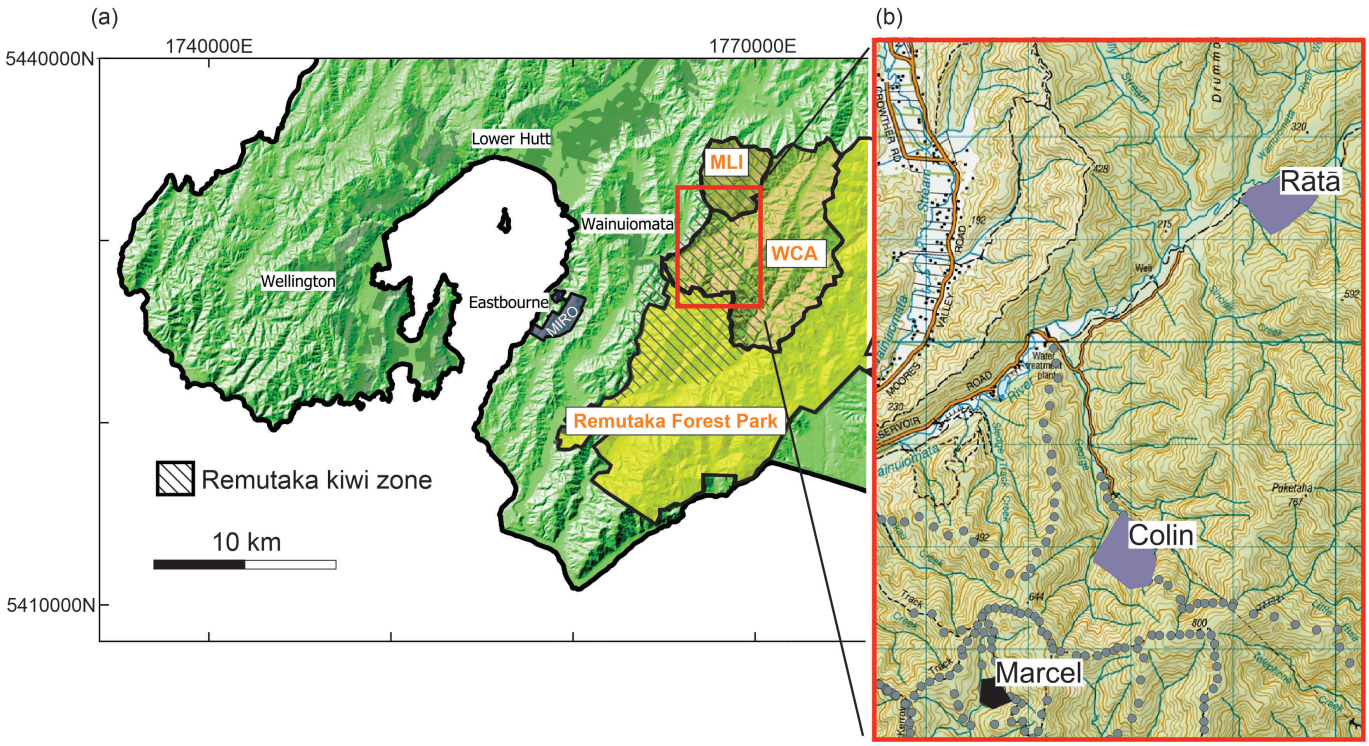

Figure 1. (a) Location of the Remutaka Forest Park (yellow shading) and the Greater Wellington Water Catchment Area (WCA) and Mainland Island (MLI) (orange shading). Also shown are nearby towns and the adjacent Mainland Island Restoration Organisation trapped area (MIRO). The region where kiwi are present—inferred from 2020 acoustic recorder surveys—is shown with a hatched pattern. (b) closeup of box from map in (a), showing approximate home ranges of Colin, Rātā, and Marcel (shaded and labelled). Grey circles are DOC 200 traps along some of the main tracks. Each grid square is 1 × 1 km (NZGD2000, NZTM projection).

Study Birds

We studied one bird with a known burrow location (i.e. a control subject) to obtain initial data for building our method, then tested the method on five unknown burrow locations belonging to two unmonitored male kiwi.

Marcel is a first-generation Hauturu translocation. At the time of our study he was fitted with a radio transmitter, and his breeding with mate Hēmi has been monitored since 2009. Their territory is in the main kiwi area in the Upper Turere Valley catchment of the Remutaka Ranges. Since Marcel's location was known, he was a control subject for this paper.

Colin is a second-generation ONE (Operation Nest Egg) bird who breeds with a first-generation female kiwi (Kiwifruit) translocated from Hauturu in 2009. Their territory is in the Wainuiomata Water catchment (an area of old growth podocarp forest) and is well-known from previous incubations, when Colin had a transmitter fitted.

Rātā is a third-generation bird born in the park, as is his partner UB15. Rātā has never been handled. Their territory is in the north-eastern part of the Wainuiomata Water Catchment adjacent to the GW mainland island, several kilometres from Colin and Kiwifruit.

Methods: Establishing calling behaviour

We were unable to find any literature concerning the anecdotal reporting that incubating male kiwi call shortly after they leave their burrow, and close to the burrow. We therefore used a male kiwi monitored by telemetry, Marcel, to check this key assumption.

Marcel's kiwi egg timer transmitter switched to incubation mode on 12 November 2019. We tracked him to the burrow and, 40 days after the onset of incubation, deployed a grid of 13 DOC AR4 omnidirectional acoustic recording units (ARUs)[1] centred on the incubation burrow, which was in a tree root close to the Turere Stream. The recorders recorded at 8 kHz sampling frequency and have 35 ± 4 dB sensitivity with a frequency response between 50 and 4 kHz. We also deployed several invisible IR (wavelengths c. 940 nm) motion-triggered trailcams around the burrow, to identify the time of departure and re-entry each night (several Campark T70 Invisible Infrared Trail Cameras and one Browning Dark ops Pro XD Trail Camera).

Acoustic recorders were fixed to trees and spaced 30 m apart along approximately N–S and E–W transects, with additional recorders to form a rectangle of points enclosing the transects (i.e. 60 m from the incubation burrow diagonally; see Appendix S1 in Supplementary Materials). One recorder (MA9) failed early and this recording location was then replaced to provide a more detailed soundscape close to the burrow. Some geographic barriers were present: a stream to the west, and a dense scrubby region to the east, while in the N–S direction, animal tracks made travel easier. The approximate locations of calls based on the relative amplitudes at each of the recorders in the grid showed that Marcel often left the burrow and travelled north along the stream bank, the path of least resistance. The data for each night were analysed to determine when Marcel left his burrow (using trailcam footage), and the time of his first call (from ARU data). For nights when Marcel called within 10 minutes of leaving the burrow, we estimated his distance from the burrow. This estimation involved a multistep process:
(1) Making sure recorders were calibrated, i.e. produced similar amplitudes for a test call when no noise was present,
(2) using a subset of calls that were clearly very close to a particular recorder (within five metres, i.e. calls that included footsteps before and after the call) as known source locations for estimating an approximate relationship between amplitude and distance,
(3) for all remaining calls, calculating the distance from each recorder using amplitude and the best-fit relationship from step 2 and triangulating to estimate the best-fit source location and its uncertainty (from intersection misfit).

This multi-step procedure is described in more detail in Appendices S5–11. The use of amplitudes to estimate distance is an approximation and does not consider the direction the bird was facing, topography, or the location of obstructions such as tree trunks. However, step 2 in the list above uses only calls that are verifiably close to a recorder. We estimate, based on detailed scrutiny and human listening to the calls later, that the maximum source location error introduced by this assumption is ± 5 m; in all the cases used for calibration in step 2, we could hear rustling and footsteps that indicated the bird was indeed close to the recorder shortly before or after the nearby call (Fig. 2).

We monitored the burrow using acoustic recorders and trailcams for 55 nights (36 days prior to hatch, and 19 days afterwards; see Appendices S2–4). Marcel's emergence from the burrow was recorded on a trailcam on 51 of those 55 nights; on 44 out of those 51 nights he emerged between 9 pm (just after sunset) and 11 pm (NZDT; Fig. 3). As the hatch date got closer, his emergence time became more variable. For the nights when we did not detect his emergence, it could be because he did not leave the burrow at all, or because his exit was missed by the camera.

We were unable to detect a male kiwi call on the ARUs on 17 nights (see Appendices S2–4). Ten of these were clear enough to analyse, but had no calls recorded within the period the ARUs were switched on, and on four occasions, coincided with nights where the trailcam did not detect him leaving (suggested that he did not leave the burrow at all). The seven additional nights had poor weather that precluded analysis of the recordings, leaving 38 nights with both trailcam burrow exits and ARU recorded calls. Of these, Marcel called less than 5 minutes after leaving the vicinity of the burrow on 22 out of the 38 nights (i.e. 58% of the time), and within 10 minutes 60% of the time (Figs 3, 4). We performed a Pearson chi-squared test on these data using three bins (called within first 10 minutes; called more than 10 minutes but less than one hour after leaving; called after more than one hour). The null hypothesis (that there was no difference to a uniform call distribution in time over the average 180 minutes we monitored after emergence) was rejected ($p < 0.0001$ with 2 degrees of freedom). Our data support the assumption that the first call of the evening is made within 10 minutes of leaving the burrow most of the time.

On many nights, rustling and footsteps could be heard on the ARU located at the burrow for the first 3 minutes after emergence. From trailcam footage, some of the rustling was due to Marcel not having fully emerged from his burrow, and he was usually engaged in covering it with sticks ("gardening"). We recorded the time Marcel left the burrow as the point when this gardening had finished.

[1] https://ftp.doc.govt.nz/public/folder/CpR1cRv_cE_rqb9ua5WRTg/electronics/Acoustic Recorders/AR4 Instructions _V1.41.pdf

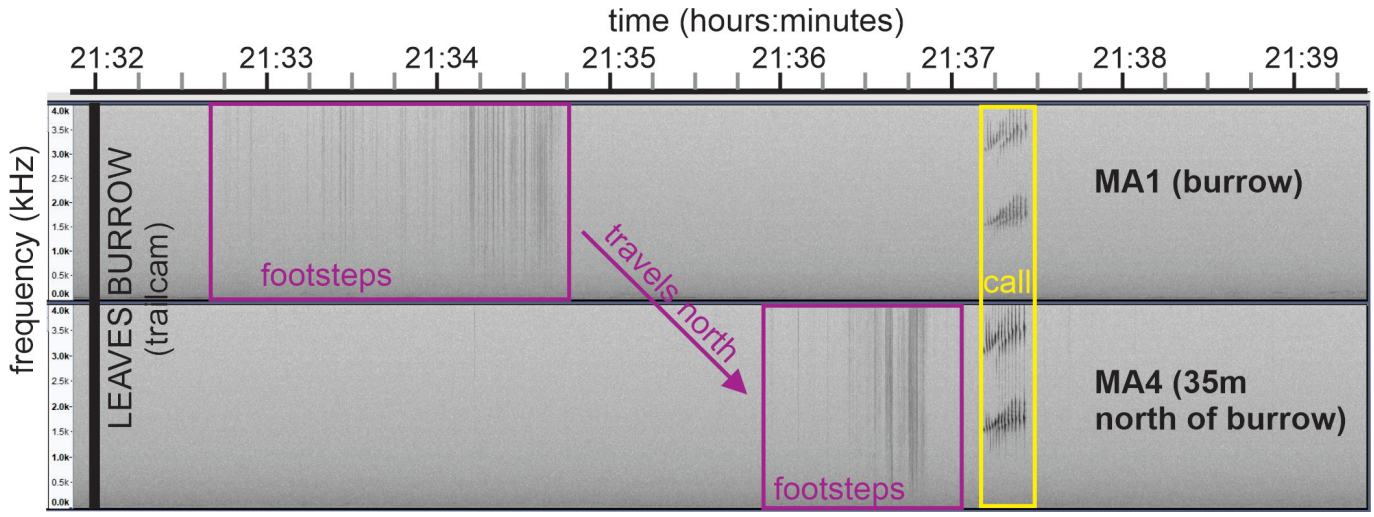

Figure 2. Marcel calibration experiment; Example spectrograms (plotted in Audacity® software https://audacityteam.org/) for stations MA1 and MA4 showing timeline between emergence (based on trailcam) at burrow (MA1) followed by footsteps (outlined in purple box) gradually fading away. Later footsteps (at site MA4, ca. 35 m north of MA1) followed by first call of evening close to MA4 (31 December 2019 at 21:37). This call was used to aid distance calibration for Fig. 4.

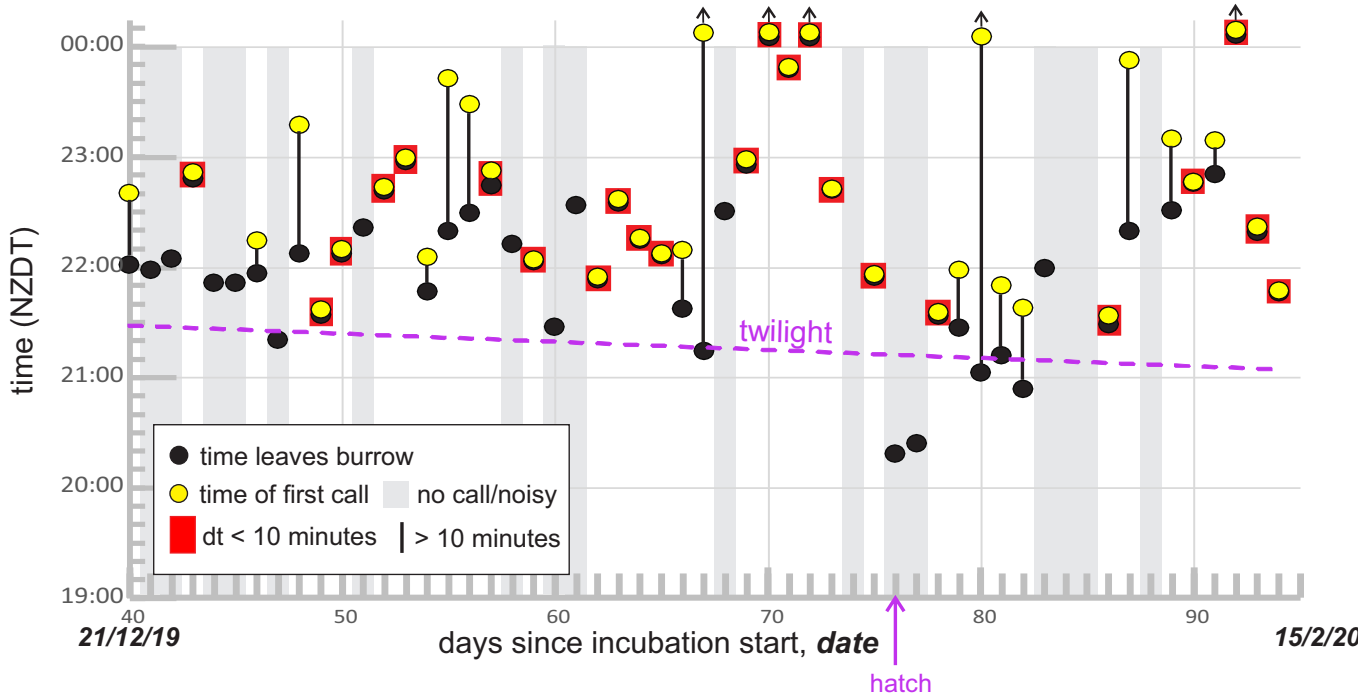

Figure 3. Marcel calibration experiment; Results showing time of emergence (black circles, identified from trailcam footage at the burrow) and time of first call (yellow circles, as detected on an ARU) plotted against days since incubation start (indicative calendar dates are in black italics). Note that some nights had no call, in which case there is no yellow circle. Red boxes highlight nights where the time difference between Marcel leaving his burrow and calling was less than 10 minutes. Grey bars indicate nights on which no call was recorded, or the weather was too bad to analyse the first call, although time of emergence on trailcam was still noted on most of these nights. Dashed purple line shows civil twilight in Wellington (https://www.timeanddate.com/sun/new-zealand/wellington). Incubation start date (12 November 2019) is based on data from the chick timer transmitter, and the plot starts 40 days after this (21 December 2019) when ARUs and trailcams were installed around the burrow. The first chick hatched on 27 January 2020 according to the transmitter data (day 76), as indicated by the purple arrow.

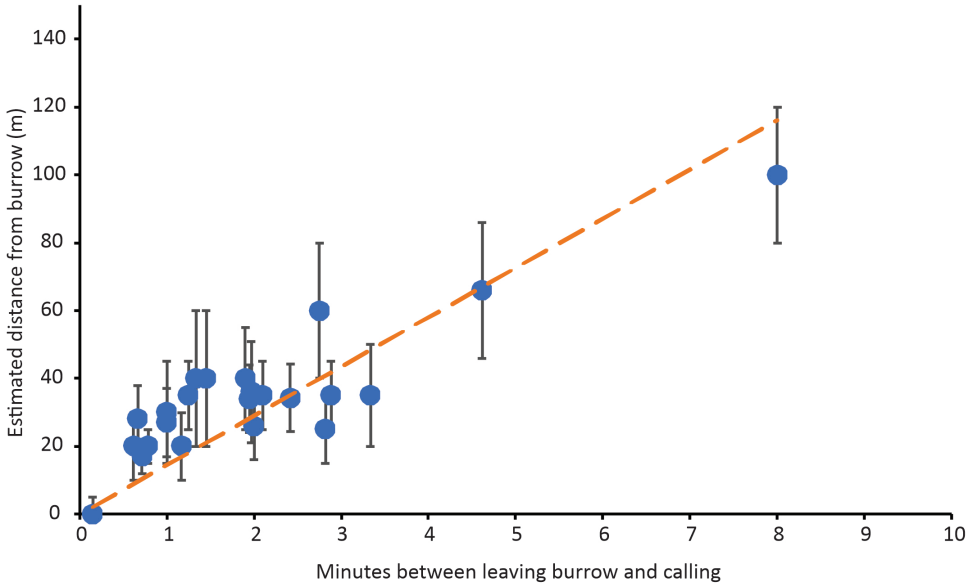

Figure 4. Marcel calibration experiment- Results showing estimate of distance travelled from the burrow before the first call of each night (based on triangulation from ARU grid using the method described in Appendix S9) plotted against time since Marcel left the burrow. Only the 23 points with calls that were within 10 minutes of leaving the burrow vicinity (Fig. 3 boxes) are plotted. Vertical error bars are the estimated uncertainty in distance from the burrow, as described in Appendix S9. A linear fit (orange dashed line) indicates that Marcel travelled at an average of 14.5 metres per minute away from the burrow before calling ($R^2 = 0.59$, P-value < 0.001).

For the 23 nights when Marcel called within 10 minutes of leaving the burrow vicinity, the estimated distance between the location of his first call and the burrow (based on triangulation from nearby recorders) is correlated with time since burrow departure (Fig. 4). Twenty of the 23 calls were within about 40 m of the burrow (and eight of these were within about 20 m). However, there is significant variability: While a linear fit gives an average of c. 14 metres travelled per minute, the R^2 is 0.59, with a maximum estimated travelling speed of 40 m min^{-1}; Fig. 4). We do not know what he was doing during that time as he was not visible on the cameras, but we assume that he was foraging and scenting. It is unlikely that he was travelling in a straight line to a destination for the purposes of calling.

In summary, for more than half the time monitored, Marcel called soon after leaving his burrow (within 10 minutes; Fig. 3) and on these nights, he was mostly at a distance less that 40 m from it (Fig. 4; Appendix S10). These close calls were mostly nearest the incubation burrow and the ARU immediately north of it (35 m away), suggesting that Marcel preferred to travel north along an easy sidle track alongside (and east of) the stream before calling. For nights with a considerable time between emergence and calling, calls were fainter, and triangulation suggests that these calls were mostly coming from > 50 m away uphill (towards the Whakanui track; Appendix S10), implying that he had already left the area around the burrow. Marcel did not call from near the ARU sites across the stream to the west, from which we infer that he did not often cross the stream.

These data support the anecdotal reports that male kiwi often make their first call close to their burrows and soon after emergence, at least during the second half of the incubation (which is all we tested). In addition, the detection of footsteps and rustling in association with nearby calls (Fig. 2) are a good indication that the kiwi is close to the ARU, and hence may be able to assist in localisation. We therefore decided to attempt to use the first call to develop a method to identify incubation burrows of non-transmittered incubating males entirely by remote monitoring methods.

Methods: Detecting an Unknown Burrow

Our method aims to use call location (and other proxies such as rustling and footsteps) to locate kiwi burrows. We outline the general procedure that we followed (Fig. 5; see Appendix S11 for an enlargement of this figure), and then describe several trials that we have successfully conducted to locate unknown incubation burrows using a combination of human listening and ARUs.

Establishing general area of incubation (to within 200m): Steps A1, A2, and B1

We based our initial ARU site locations on results from previous acoustic surveys that indicated the presence of a duetting kiwi pair in the study region (Fig. 5, flowchart step A1), deploying 4–8 AR4 acoustic recorders set to record for the whole night (Fig. 5, flowchart step A2). Start dates for this step were based on historical data about average incubation onset for the mixed lineage brown kiwi residing in the Remutaka Forest Park previously radio tracked (late July–early September for first incubations; November–February for second incubations) supplemented by previous breeding history of the particular kiwi when known from prior radio tracking data. We used easily accessible tracks and ridges with a good sound-view for this first deployment (Fig. 5, flowchart step A2). These initial recordings were collected every week for several weeks and the spectrograms analysed to identify:
(1) The time of the first call of the evening,
(2) the relative amplitude of this call at each recorder,
(3) whether noise (wind and rain) made call detection problematic, in which case that day's record was discarded,
(4) the final male call before dawn.

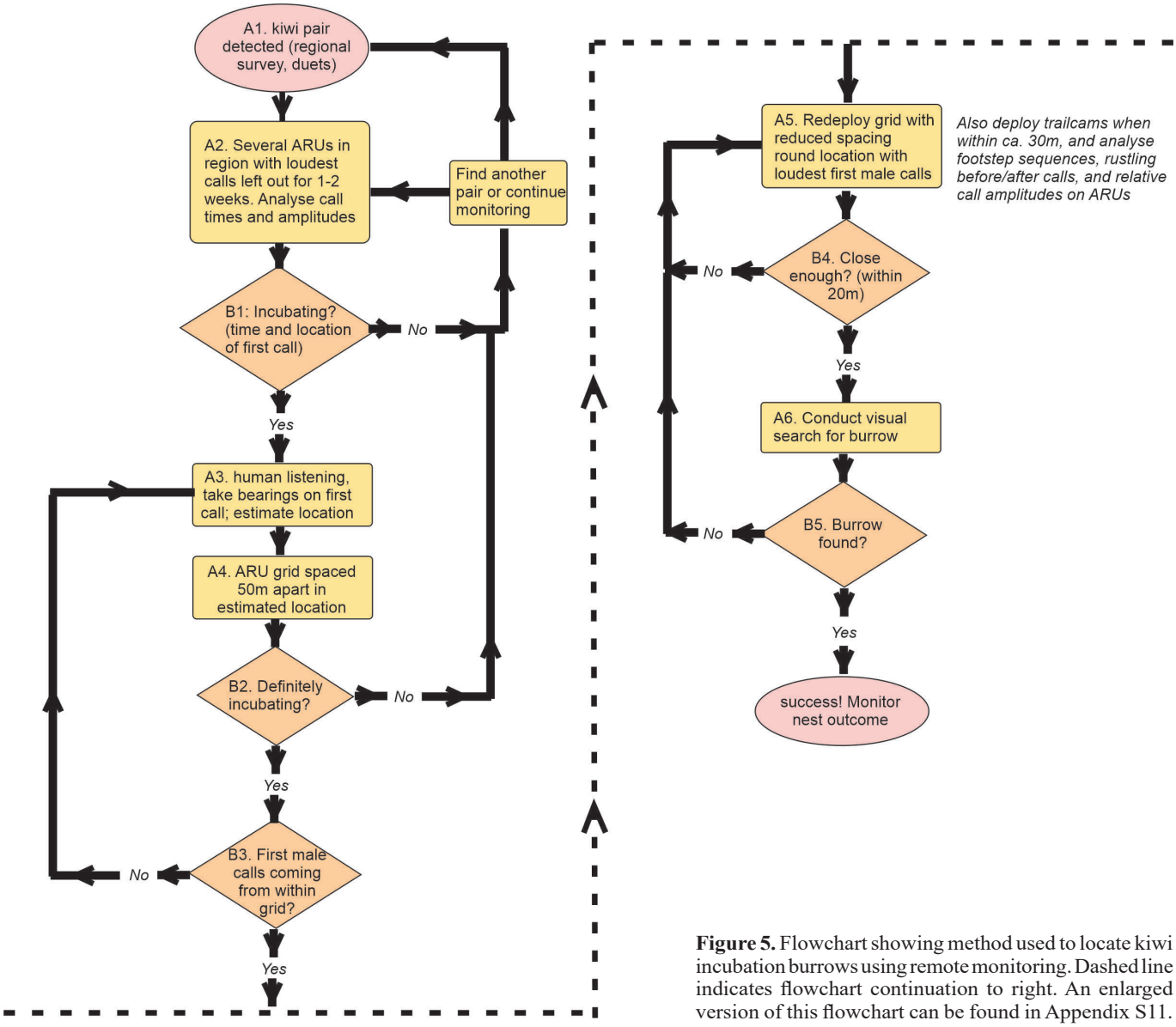

Figure 5. Flowchart showing method used to locate kiwi incubation burrows using remote monitoring. Dashed line indicates flowchart continuation to right. An enlarged version of this flowchart can be found in Appendix S11.

We first needed to determine whether the male was likely incubating or not (Fig. 5, flowchart step B1). Positive signs of incubation include fairly consistent call location (as shown by triangulation from human listening or call amplitude at nearby ARUs; while North Island brown kiwi can use the same non-incubation burrow on successive nights we have found it be relatively uncommon in this population) and a drop in minimum nightly activity time (as measured by the number of hours between the last and first call of each night) (Taborsky & Taborsky 1999; Cunningham & Castro 2011). For example, on the nights of 19–21 August 2019, one of the male kiwi subjects, Rātā, was active for a minimum of 8–9 hours per night and was deemed not to be incubating, whereas from 25 August through September his minimum activity time dropped to an average of 5–7 hours. Based on this drop we estimated the start of incubation to be c. 20 August, which is roughly consistent with the (later) documented first chick hatch 80 days later.

While establishing the general location of the burrows, we made use of the fact that up until late in the incubation period, the male kiwi emerges within the first hour after twilight at least half of the time (e.g. as shown in the previous section, for 50% of calls from day 40 until day 66 (10 days before hatch) on Fig. 3; see also Appendix S14 showing calls just after twilight are even more common during the first 40 days of incubation). Once incubation was clearly underway, the near-dusk calls generally came from a consistent area that we could roughly pinpoint to within 200 m using the relative amplitudes (volume intensity) at the ARU locations.

The AR4 recorder has a single omni-directional microphone, and so it is not possible to estimate direction when they are too widely spaced for triangulation (step A3). A rough estimate of calling distance from bird to recorder can be made where topographic barriers are not significant, as was described in the previous section. Barriers such as prominent ridges can obscure calls and/or estimates of call distance, but conversely can help inform direction because calls coming from the other side of a significant barrier will not be detected. We supplemented this with human listening to take bearings, from sites co-located with the ARUs that had

the loudest calls at this stage, to further pinpoint the region the call was emanating from (Fig. 5, flowchart step A3). Once the recorder site(s) with the loudest calls were identified and we had estimated the burrow location to within 200 × 200 m, we moved to the next step.

Grid refinement plus human listening: Steps A3, A4, B2 and B3

Between nine and 20 AR4 recorders were placed in an approximate grid around the region with loudest calls, c. 50 m apart (Fig. 5, flowchart step A4). While most of the ARUs were programmed to record for 2–3 hours after sunset, 1–2 of them were left to record all night to refine estimates of foraging time and verify that the male was in fact incubating (Fig. 5, flowchart step B2). To supplement the recorders, for some trials we returned to using human listening on 4–8 nights per study area (flowchart step A3) during the first few hours after twilight so that we could take compass bearings on calls (Fig. 5). One to three human observers (mostly experienced kiwi handlers) would travel to the study site and situate themselves at good vantage points prior to sunset. They would then listen for up to two hours for nearby kiwi calls and estimate distance and direction to those calls. Where more than one listener was involved, triangulation using compass bearings provided more precise estimates of the location of the call. This combination of call amplitude measurement and triangulation led to a refined estimate of first call area. If calls soon after twilight were within the grid (i.e. within a 50 × 50 m area), we proceeded to the next step; otherwise, we moved the grid to focus on the revised call area and repeated the procedure (Fig. 5, flowchart step B3).

Further grid refinement including trailcams and detection of footsteps: Steps A5 and B4

A dense grid of 9–20 AR4 acoustic recorders was deployed in the area where a burrow was thought to be located based on the previous steps and spaced ca. 15–25 m apart (Fig. 5, flowchart step A5). The recorders were calibrated for amplitude prior to use and set to record for the first 2 hours after sunset. The SD cards from the recorders were collected every few days, and the recordings were analysed in a two-stage process:
(1) Spectrograms of the acoustic recordings were viewed, and the time of first call and relative amplitudes were measured. Noisy nights (wind, rain) and nights where the first call was more than two hours after twilight were not analysed,
(2) the nearest recorder to each first call was identified by comparing maximum dB of the call (against background noise), signal intensity (brightness of the energy curve in the spectrogram), and the number of harmonics, across the various recorders (see Fig. 2).

When reviewing these recordings, we looked and listened not just for the kiwi calls, but also indications of close movement: footsteps and rustling sounds. Footsteps associated with the first call and sequentially detected at adjacent recorders allowed us to establish direction of travel and backtrack towards the point of origin. Our refined grid was also sometimes informed by kiwi detected not long after twilight on trailcams strategically placed at stream crossings, logs, and clearings. Using trailcams is challenging due to trigger slowness and the inability to capture a large potential area the kiwi could be moving through, but we found them useful for example at stream crossings, since these indicate the direction the kiwi was moving. Trailcams co-located with recorders also helped us to distinguish kiwi footsteps from other night sounds e.g. rustling from rats.

Our aim was to pinpoint the likely location of the burrow to within a searchable area, which we judged to be within c. 20 m depending on terrain and vegetation cover (Fig. 5, flowchart step B4), so this step was repeated by re-centering recorders and trailcams in the grid with a smaller spatial distance between them until this criterion was met ("bracketing" in the mathematical optimisation literature). At the end of the procedure, we had narrowed down the approximate location of the burrow to within c. 20 m.

Final stages—visual inspection of area: Steps A6 and B5

In the final step, trained kiwi handlers visited the area in the daytime and systematically searched the prospective burrow region to locate the burrow by sight (Fig. 5, flowchart step A6). North Island brown kiwi incubation burrows are generally recognisable from around 1–2 m because they have prominent entrances without cobwebs, are covered by a few fern fronds, and have kiwi feathers and scat visible. Some can even be detected by the human sense of smell at close range (of course, this may not be true for other species and taxa). Care was taken to carefully inspect banks covered in vegetation and to avoid disturbing the birds (hence use of trained kiwi handlers). We confirmed we had found the burrow by smell and low-light photography (manual camera at the burrow entrance). Following successful location of the burrow (flowchart step B5), we monitored breeding results using an invisible infrared (IR) trailcam pointed at the entrance until the kiwi chicks left the burrow.

Results of three completed trials

Three trials were carried to completion where we successfully found the incubation burrow. We also initiated two additional trials that terminated early -we describe these in the next section.

Of the successful trials, the first (Trial R1, Rātā) ran from mid-September to early November 2019 (2 months from initial search to location of burrow), while the second (Trial C2, Colin; Fig. 6) was slightly shorter, from November 2019 to early January 2020. The third (Trial C3, Colin) took us only 1 month (September 2020) to find the burrow. Detailed illustrations of each trial are reproduced in Appendices S12 to S21.

Each site was visited twice a week during the trial to collect SD cards from the recorders, reposition recorders and/or cameras, and to obtain bearings. In addition to this time in the field, approximately 3–4 hours were spent after each visit to identify the kiwi calls in the multiple recordings, identify the loudest, and review trailcam footage. One complicating factor experienced in one of the successful trials was the presence of a second male in the area. For trial R1 (Appendix S12–14) this significantly delayed the flowchart steps between A3 to A5 in Fig. 5 because of confusion as to which male was calling. In this first trial, inexperience in using the technique meant that we thought we were closer to the burrow than we really were, so we moved too early to visual inspection (step A6). On the other hand, trial R1 also had the most successful use of back-tracking of kiwi footsteps and trailcam footage, which helped constrain the direction in which Rātā was travelling early in the evening.

Trial C2 (Fig. 6; Appendices S15–19) was the most thorough test of the method, because the burrow was located a long way down a side ridge in challenging vegetation. We

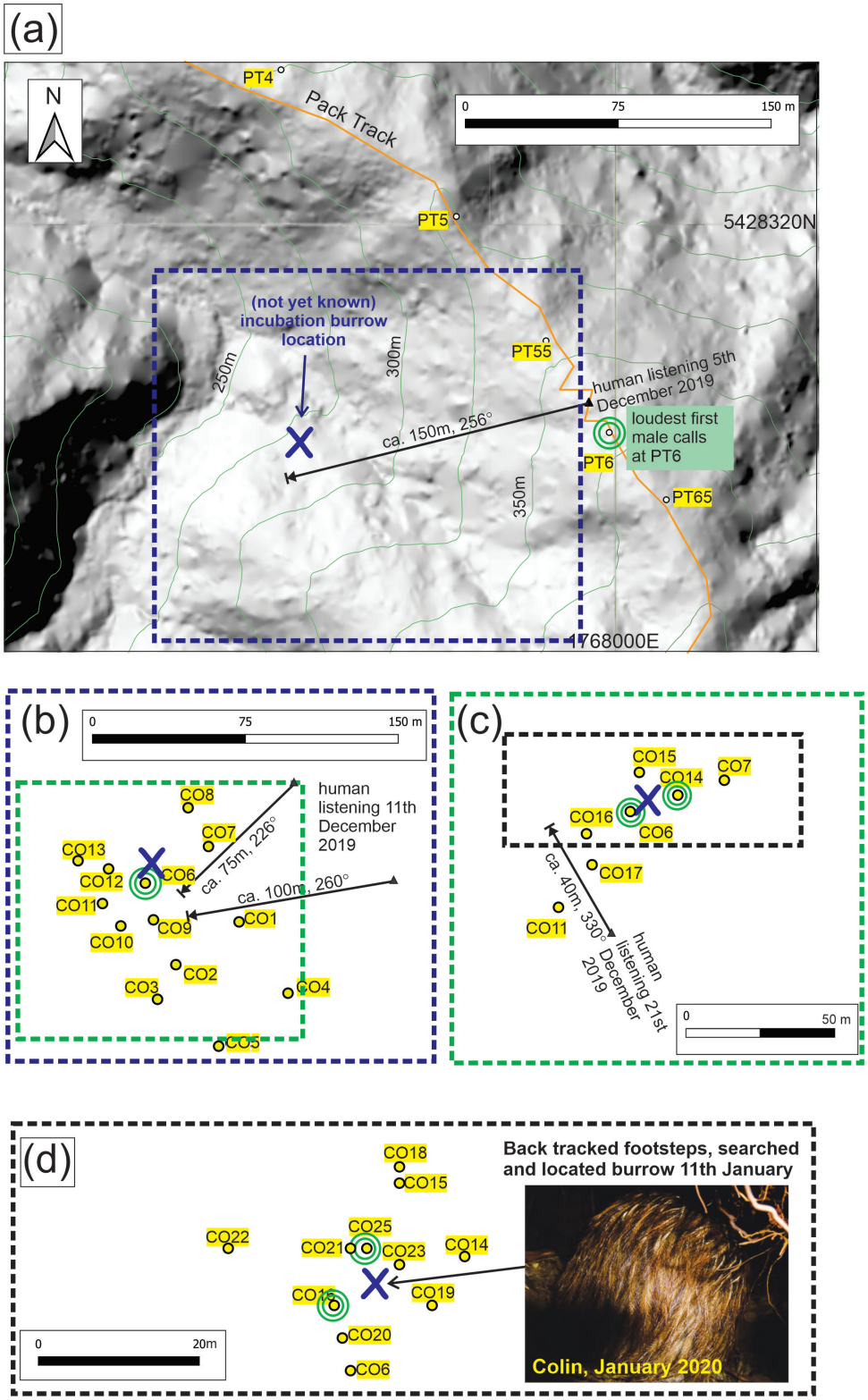

Figure 6. Example of method to locate kiwi incubation burrow using remote monitoring (Trial C2, Colin's incubation, 5 December 2019 to 11 January 2020). (a) Initial deployment of 5 ARUs along a track close to the burrow (the Pack Track; locations marked as circles) from 5–21 December 2019 plus human listening near the recorder with the loudest calls projected c. 150 m to the west. Background hill shading from 1 m DEM lidar data (https://data.linz.govt.nz/layer/53621-wellington-lidar-1m-dem-2013-2014/). For reference, the eventual located burrow (then unknown) is shown by the blue X. The blue dashed box in (a) outlines the closeup in (b) that shows the next iteration from 21–29 December 2019 (step A4 on flowchart from Fig. 5) with 13 ARUs spaced c. 20 m apart, plus two bearings from human listening. Green concentric circles indicate the recorder with loudest calls. The green dashed box outlines the closeup in (c) which shows deployment 3 from 29 December 2019–1 January 2020 plus one human bearing. A closeup in (d) of the black dashed outlined box in (c) shows the final iteration (step A5 on Fig. 5) followed by visual inspection (Step A6 on Fig. 5) which led to successful location of the burrow on 11 January 2020. Inset shows photo of Colin in his burrow taken on the day we found it. A more detailed illustration of this trial can be found in Appendice S15–S19 in the Supplementary Material.

spent a long time iterating between steps A5 and A6 because the burrow was hidden in a bank. Trailcams, footsteps, a strong kiwi smell and a systematic search eventually led us to the burrow.

The case where we found the burrow fastest (Trial C3, September 2020; Appendices S20–21) was aided by the burrow being located only 2 m off a track, close to an ARU location regularly used for monitoring. Kiwi footsteps and trailcams were used to narrow down the region of interest.

Trials Terminated Early

In two cases we abandoned our attempts early because of complicating factors. In the first Colin trial (C1, August–early September 2019) we gave up because a sub-adult male was spending time in the breeding pair's territory, making it difficult to determine which male was calling. Also, at this point we had not established that our key assumption (that the male kiwi call close to their incubation burrow soon after emergence at night) was correct, making us doubt the method. In October–November 2020 we initiated another trial to locate Rātā's burrow (Trial R2), but foraging times and lack of consistency in call locations suggested that he was not incubating during this time (i.e. the answer to Fig. 5, step B1 was 'no') so we did not continue the trial. With hindsight from these abandoned trials, much wasted effort can be avoided if the decision to cease a trial is made early. If the aim is to find 1–2 nests for monitoring and the exact kiwi involved is not so important, we suggest starting out with multiple different kiwi pairs, and focusing effort on the one most likely to succeed once past the initial stages (steps A1–A2, Fig. 5).

Discussion

Acoustics, some cameras, and a lot of human effort can locate an incubation burrow, at least in a reasonably low-density population, where no more than 2–3 kiwi are calling in an area; Taborsky & Taborsky (1992); Pierce & Westbrooke (2003). The method described here is currently quite labour intensive, but has several advantages over other methods, primarily that it can be used in breeding season when dog searches are not permitted, and that it can use semi-skilled volunteers who do not need to be licensed to handle kiwi (although see note of caution below). However, several disadvantages became apparent during our trials:

(1) The method requires multiple deployments of recorders and is time-consuming. It is best suited to accessible kiwi populations, i.e. those which do not require more than 1 hour to walk to),

(2) topographic effects can influence call detection and challenge analyses,

(3) stray incursions by subadult males seem to be common and possibly more so when the male is incubating, because he cannot defend his territory. The female sometimes duets with the invading subadult, making tracking burrows through calls more difficult, especially in higher density populations,

(4) directional tracking using human listening is not ideal, because it requires people to sit for long periods in the cold and dark. Human listening cannot be used in the final few iterations (within 30–50 m of the burrow) since in our experience, the presence of humans nearby often prevents the male from calling (sometime for the entire night even when they were only present for 1–2 hours after dusk).

The final stage of the procedure requires humans to approach a kiwi burrow without knowing precisely where it is, which may disturb the kiwi and care must be taken to avoid stepping on it or making too much noise; this caution applies equally to other methods of finding incubation burrows (Ziesemann et al. 2011). While people who are not kiwi handlers can participate in the earlier and most time-consuming parts of the method, we recommend that the final iteration and visual inspection for burrows be carried out by trained kiwi practitioners.

Nevertheless, the results here establish proof-of-concept. To become more practically useful, the following improvements are needed:

(1) Acoustic localisation methods, at least directional tracking using multilateration or time-of-flight or a sensor array, as used in e.g. Mennill et al. (2006) and Collier et al. (2010), would speed the process up significantly, requiring fewer iterations and fewer recorders,

(2) automated software processing, e.g. in (AviaNZ Marsland et al. 2019), to identify calls and estimate the energy in the call can reduce the effort required. This could include the automated detection of footsteps and rustling,

(3) individual call recognition could remove the issue of more than one kiwi male in the area, see e.g. Dent & Molles (2016) for great spotted kiwi (*Apteryx haastii*) and Digby et al. (2014) for little spotted kiwi (*Apteryx owenii*),

(4) better research knowledge of sound propagation in forest landscapes would make detection of calls near a kiwi burrow (based on triangulation from directional arrays) easier to calculate,

(5) trailcams with shorter lag times would reduce the number of missed detections.

These improvements could make the method described here more practicable. Monitoring 2–3 kiwi pairs per breeding season using this method—with associated collection of trailcam footage and calls—can be used to estimate breeding attempts and foster community interest for ongoing support, sponsorship and trapping efforts. The fact that male kiwi often call near their incubation burrow provides a method to refine the mapping of kiwi home ranges. If, for example, procedures A1–A4 of Fig. 5 are used without proceeding to refine and search for the burrow, then the kiwi burrow can be estimated within a 50 × 50 m zone, facilitating mapping of kiwi home ranges and pairs. We emphasise that care must be taken to choose an appropriate ARU spacing depending on the required outcome, since the final stages of the method (where multiple ARUs are located close to the incubation burrow) must be done carefully to avoid disturbance of the nest- this should only be carried out by experienced kiwi practitioners. Furthermore, great care must be taken when using the method during the earliest stage of incubation when the male is most prone to abandonment of the nest if disturbed. The kiwi best practice manual, for example, states that camera traps must only be set up at nests when they have been occupied for at least 20 days, should be no closer than 3 m to the burrow, and that no more than three cameras should be trained on the incubation burrow for monitoring purposes (Colbourne et al. 2020).

North Island brown kiwi make ideal subjects for this study because they are largely pair territorial, with large territories, incubation is by the male alone, and they exhibit reliable calling habits. Other species of kiwi, let alone other taxa, may not share these characteristics, for example changes in calling behaviour (Colbourne & Digby 2016). The use of footstep back-tracking may also be challenging if weka (*Gallirallus australis*), which are likely to have similar footstep sounds to kiwi, are present. However, as we improve the method, particularly to identify

direction effectively, it may be that it can be adapted for other species; though more caution may be required, since other kiwi species are more easily disturbed during the breeding season, e.g. great spotted kiwi; Toy & Toy (2021).

In summary, North Island brown kiwi males frequently call close to their incubation burrows on emergence in the evening during the second half of the incubation period (about 60% of the time for our control subject). By selecting male calls clustered in location during incubation season and checking for signs of incubation, it is possible to use remote monitoring methods with acoustic recorders, trailcams and human listening to locate incubation burrows. We have outlined a method for this approach and demonstrated its use by successfully locating three incubation burrows in 2019–2020 in the Remutaka Forest Park near Wellington, New Zealand. With technical improvements this method holds great promise for providing an alternative way to monitor breeding outcome of North Island brown kiwi without the need for trained kiwi dogs to detect burrows.

Author contributions

SE formulated the hypothesis. SE and SM co-designed the experiments and conducted the field work. SE analysed the data. Both authors contributed to interpretation and writing.

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Supplementary material

Additional supporting information may be found in the supplementary material file for this article:

Appendix S1. Layout of the control experiment (Marcel, December 2019–February 2020).

Appendix S2. Summary of nights observed of the control experiment (Marcel, December 2019–February 2020).

Appendix S3. Overview of the control experiment (Marcel, December 2019–February 2020).

Appendix S4. Summary of causes for the seven nights with insufficient information for analysis of the control experiment (Marcel, December 2019–February 2020).

Appendix S5. Outline of the procedure used to estimate distance travelled by Marcel from the incubation burrow for each call.

Appendix S6. Summarising six nights of activity that had calls very close to an ARU

Appendix S7. Linear fit to dB vs. distance from source based on amplitudes at each ARU station and distance.

Appendix S8. Distances to source calculated for the night of 10 January 2020 from nearby ARU stations.

Appendix S9. Triangulation plot for the night of 10 January 2020 with coloured circles showing estimated distance to Marcel's first call of the evening from nearby ARU stations.

Appendix S10. ARU stations, calls < 10 minutes after leaving burrow and > 10 minutes after leaving burrow (grey triangles; call area outlined with grey dashed polygon).

Appendix S11. Enlargement of flowchart of method to locate kiwi burrows using remote monitoring.

Appendix S12. Successful trial R1, Rātā's incubation, September to November 2019.

Appendix S13. Trial R1, Rātā's incubation, September to November 2019.

Appendix S14. First evening call times for Rātā over the course of the incubation for trial R1, compared to civil twilight.

Appendix S15. Trial C2, Colin's incubation, December 2019 to January 2020.

Appendix S16. Trial C2, Colin's incubation, December 2019 to January 2020 (initial grid of ARUs).

Appendix S17. Trial C2, Colin's incubation, December 2019 to January 2020 (refinement of ARUs).

Appendix S18. Trial C2, Colin's incubation, December 2019 to January 2020 (further refinement of ARUs).

Appendix S19. Trial C2, Colin's incubation, December 2019 to January 2020 (narrowing region of interest).

Appendix S20. Trial C3, Colin's incubation, August to September 2020.

Appendix S21. Trial C3, Colin's incubation, August to September 2020 (refined grid of ARUs).

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