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Development of known-fate survival monitoring techniques for juvenile wild pigs (*Sus scrofa*)

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Abstract

Context. Wild pigs are an invasive species linked to numerous negative impacts on natural and anthropogenic ecosystems in many regions of the world. Robust estimates of juvenile wild pig survival are needed to improve population dynamics models to facilitate management of this economically and ecologically important invasive species. Despite this critical knowledge gap, to date no successful known-fate study of wild piglet survival (<5 months of age) has been conducted, due to a lack of appropriate method for this species.

Aims. To aid in locating and tagging neonates, we piloted the use of vaginal implant transmitters (VITs) in adult wild pigs and evaluated average retention times of stud ear-tag transmitters, clip ear-tag transmitters, sutured and epoxied transmitters, harness transmitters, and surgically implanted transmitters to monitor known-fate survival of piglets.

Methods. We captured pregnant female pigs and implanted them with VITs. We tagged subsequently located neonates and piglets captured in traps with the aforementioned transmitters and monitored them to determine retention times and feasibility of each method.

Key results. VITs were effectively used to determine the location and time of wild pig parturition, allowing counting and tagging of neonate wild pigs. Stud ear-tag and abdominal implant transmitters were well retained by piglets weighing ≥3 kg, in contrast to the other tested transmitters.

Conclusions. Stud ear-tag and abdominal implant transmitters allowed known-fate monitoring of juvenile wild pigs, although, of these, stud ear-tag transmitters may be more practical as they do not require field surgery on piglets. Due to their relatively large size, the stud ear tag transmitters were infeasible for monitoring of true neonates (~1 kg); however, this application method may be suitable for neonates upon development of lighter-weight transmitters. The other transmitter attachment methods we tested were ineffective for monitoring of piglet survival, due to poor retention of transmitters.

Implications. The techniques piloted in this study will facilitate research into the reproductive ecology of wild pigs and known-fate studies of piglet mortality to aid in population modelling and evaluation of cause-specific mortality and factors affecting survival of these often-invasive animals.

Additional keywords: attachment, neonate, piglets, radiotransmitter, survival, *Sus scrofa*, vaginal implant transmitter, wild pigs.

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Introduction

Wild pig (*Sus scrofa*) populations and Eurasian wild boar – from which pigs descend – have been rapidly growing in abundance and geographic distribution over the past few decades globally (Bevins *et al*. 2014). This species has been introduced throughout numerous parts of the world (e.g. Africa, Australia, North America), and is frequently considered invasive, due to its negative impacts on native ecosystems (Barrios-Garcia and Ballari 2012; Bengsen *et al*. 2014). These impacts include deleterious effects on the local environment and wildlife through degradation of habitat, predation of and competition with native wildlife species, and transmission of infectious diseases (Campbell and Long 2009; Barrios-Garcia and Ballari 2012; Bevins *et al*. 2014; Keiter and Beasley 2017). Beyond disease risk, wild pigs and wild boar also pose a threat to human health due to their increasing involvement in vehicle collisions (Beasley *et al*. 2013; Sáenz-de-Santa-María and Tellaría 2015). Research has linked the population density of this species to the magnitude of its impact on ecosystem and human health (Gortázar *et al*. 2006; Beasley *et al*. 2013; Krull *et al*. 2016), requiring improved knowledge of wild pig population dynamics to better evaluate risks posed by this species.

Wild pigs have the highest reproductive potential of any ungulate in North America (Taylor *et al*. 1998), and their life history traits more closely resemble those of small mammals or passerine birds than other ungulates (i.e. high reproduction, low survival; Servanty *et al*. 2011). Similar to other ungulates, however, adult survival of wild pigs and wild boar is generally higher and more constant than that of juveniles (Bieber and Ruf 2005; Hanson *et al*. 2009; but see Toïgo *et al*. 2008). For this reason, survival of juvenile wild pigs, or piglets, might be a strong driver of population dynamics in this species (Bieber and Ruf 2005; Servanty *et al*. 2011; Mellish *et al*. 2014). Despite the importance of juvenile survival rates to population models, few studies have quantified piglet survival (Table S1, available as supplementary material to this paper); instead, studies of wild pig and wild boar population dynamics often base survival rates for piglets upon expert opinion (Servanty *et al*. 2011) or exclude animals of younger age classes (Hanson *et al*. 2009). Of the few conducted studies of piglet survival, many employed capture–mark–recapture techniques and harvest data (Table S1), despite a known bias in live-capture rates of wild pigs that likely also exists in harvest rates (Toïgo *et al*. 2008; Williams *et al*. 2011). Therefore, known-fate survival studies, in which radiomarked animals are known to be live or dead at every occasion of interest (e.g. Hayes *et al*. 2009), are needed to provide more robust estimates of juvenile survival. However, previous research has highlighted the difficulty of monitoring piglet survival and the necessity of developing techniques to determine when and where parturition has occurred to allow tagging of piglets, and to subsequently monitor survival of juveniles (Baubet *et al*. 2009). Due to the lack of methods to accomplish these objectives, no successful known-fate study has been conducted on piglets less than approximately 5 months old (Keuling *et al*. 2013).

The success of a transmitter attachment mechanism to monitor animal survival depends greatly upon the morphology and behaviour of the focal species. As such, numerous methods to attach transmitters have been developed and used in wildlife studies, including neck collars (Diefenbach *et al*. 2003), ear-tags (Keuling *et al*. 2010), suturing (Dreitz *et al*. 2011), epoxy (Fedak *et al*. 1983), harnesses (Hubbard *et al*. 1998) and surgical implantation inside the study animal (Hernandez *et al*. 2010). Neck collars, a frequently used attachment type, are infeasible in juvenile wild pigs due to their morphology (i.e. the head is approximately the same size as the neck) and rapid growth, necessitating evaluation of other potential attachment mechanisms. The overall size or weight of a transmitter must also be considered, as transmitters above a threshold size might affect animal behaviour (Aldridge and Brigham 1988) or bias estimates of demographic rates (Warner and Etter 1983). Another potential hurdle to monitoring survival of juvenile wild pigs is the risk of researcher-induced abandonment of piglets by the mother; in France, Baubet *et al*. (2009) documented high rates of litter abandonment (50% of occasions) during or immediately following tagging of piglets with radio-transmitters. Natural abandonment (i.e. uninfluenced by human presence or activities) of piglets has also been documented and occurs when a piglet cannot keep up with the associated female and litter, resulting in its separation and subsequent mortality (Barrett 1978). Therefore, when evaluating the feasibility of a technique to monitor known-fate survival of juvenile wild pigs, it is necessary to consider the following: (1) the attachment mechanism used; (2) the relative size of the transmitter; (3) the invasive nature of the tagging procedure; and (4) the amount of time required to complete the tagging.

In this paper, we present the first use of vaginal implant transmitters (VITs) in wild pigs. We tested the use of these VITs to determine wild pig parturition date and location, thereby allowing tagging of neonate wild pigs, and we evaluated the effectiveness of several combinations of transmitter units and mechanisms of attaching very high frequency (VHF) radio-transmitter units to wild piglets for known-fate monitoring. These methods included use of the following: (1) stud ear-tag transmitters; (2) clip ear-tag transmitters; (3) sutured and epoxied transmitters; (4) harness transmitters; and (5) surgically implanted transmitters. We compared these attachment techniques in terms of retention time and feasibility constraints affecting their success as tools for monitoring survival of piglets. Finally, we discuss implications and potential applications of the techniques.

Materials and methods

Study area

We conducted this research at the Savannah River Site (SRS), a 78 000-ha USA Department of Energy facility on the South Carolina–Georgia border, USA. Habitat on the SRS is managed by the USDA Forest Service (USFS) and is composed mostly of upland pine forests, with areas of bottomland hardwood and swamps characteristic of much of the south-eastern USA (Imm and McLeod 2005). Wild pigs on the SRS are the descendants of feralised domestic pigs that were released when the public, including farmers, were moved from the SRS in 1952, although the population shows morphological signs of genetic introgression by wild boar (Gaines *et al*. 2005; Mayer and Brisbin 2008). In an effort to reduce damage to habitat, contractors of the USFS have controlled wild pigs lethally on the SRS through live-trapping and termination, and hunting with dogs since 1952 (Mayer and Brisbin 2008).

VIT Deployment

All capture and handling of animals was conducted in compliance with the University of Georgia's Animal Care and Use Committee (Permit: A2015 05-0004-Y2-A1). From December 2013 to July 2016, we captured wild pigs in corral or box traps baited with whole corn. We immobilised adult and subadult animals via dart rifle (X-CALIBER, Pneudart, PA) using a combination of Telazol (4.4 mg kg^{-1}; MWI Veterinary Supply, ID) and Xylazine (2.2 mg kg^{-1}; Wildlife

Pharmaceuticals Inc., CO). We determined the age of captured individuals through examination of dentition (Mayer 2002*a*). We also recorded sex and collected a tissue sample for future genetic analyses. We assessed whether captured females of $\geq$27 kg (Servanty *et al*. 2011) were pregnant, using a portable ultrasound (SeeMore USB, Interson Corporation, CA). We implanted pregnant females with a 21-g VIT (M3930; Advanced Telemetry Systems (ATS), Isanti, MI; Fig. 1) in a manner similar to previous studies of white-tailed and mule deer (e.g. Bishop *et al*. 2011; Kilgo *et al*. 2012). These VITs incorporate a thermistor that senses and signals the temperature change resulting from the transmitter's expulsion during parturition, and that also indicates the number of half-hour intervals elapsed since the temperature change (birth; Kilgo *et al*. 2012). In short, VITs were inserted into the vagina within a sterilised, rigid clear plastic tube and extruded using a metal plunger; we oriented the wings of the VIT laterally within the animal. To facilitate monitoring, we attached a VHF collar (Model M2520B, ATS) to females implanted with a VIT; because the VHF collar is externally attached, it can transmit a signal greater distances, allowing for easier location of the implanted female. We monitored VITs 4–7 times weekly until the occurrence of parturition.

Tagging of piglets

We captured juvenile wild pigs using two techniques: (1) with adult or subadult wild pigs in box or corral traps baited with whole corn; and (2) by hand at the farrowing nest, which we located through use of VITs shortly after parturition. *Sus scrofa* is one of few species known to create farrowing nests, and it is suspected that female movements are reduced during farrowing and for a short period of time following parturition (Mayer *et al*. 2002*b*). The only previous study to attempt to tag piglets at the farrowing nest encountered high rates of researcher-induced abandonment of piglets by females, resulting in rapid mortality of tagged animals (Baubet *et al*. 2009). In an attempt to avoid this outcome, we waited 2–3 days following parturition to tag piglets at the farrowing nest, in the hope that greater bonding might occur between the female and piglets. We tracked VITs to farrowing nests and captured piglets by hand; in each case the female fled, allowing us to tag the piglets. During tagging, we attempted to limit disturbance that might attract predators or cause abandonment of piglets by minimising noise and placing captured piglets in pillowcases with attached zippers. We assessed proximity of the female to the farrowing nest using telemetry during tagging of piglets, and found that in each case the female remained relatively close (estimated $\leq$300 m).

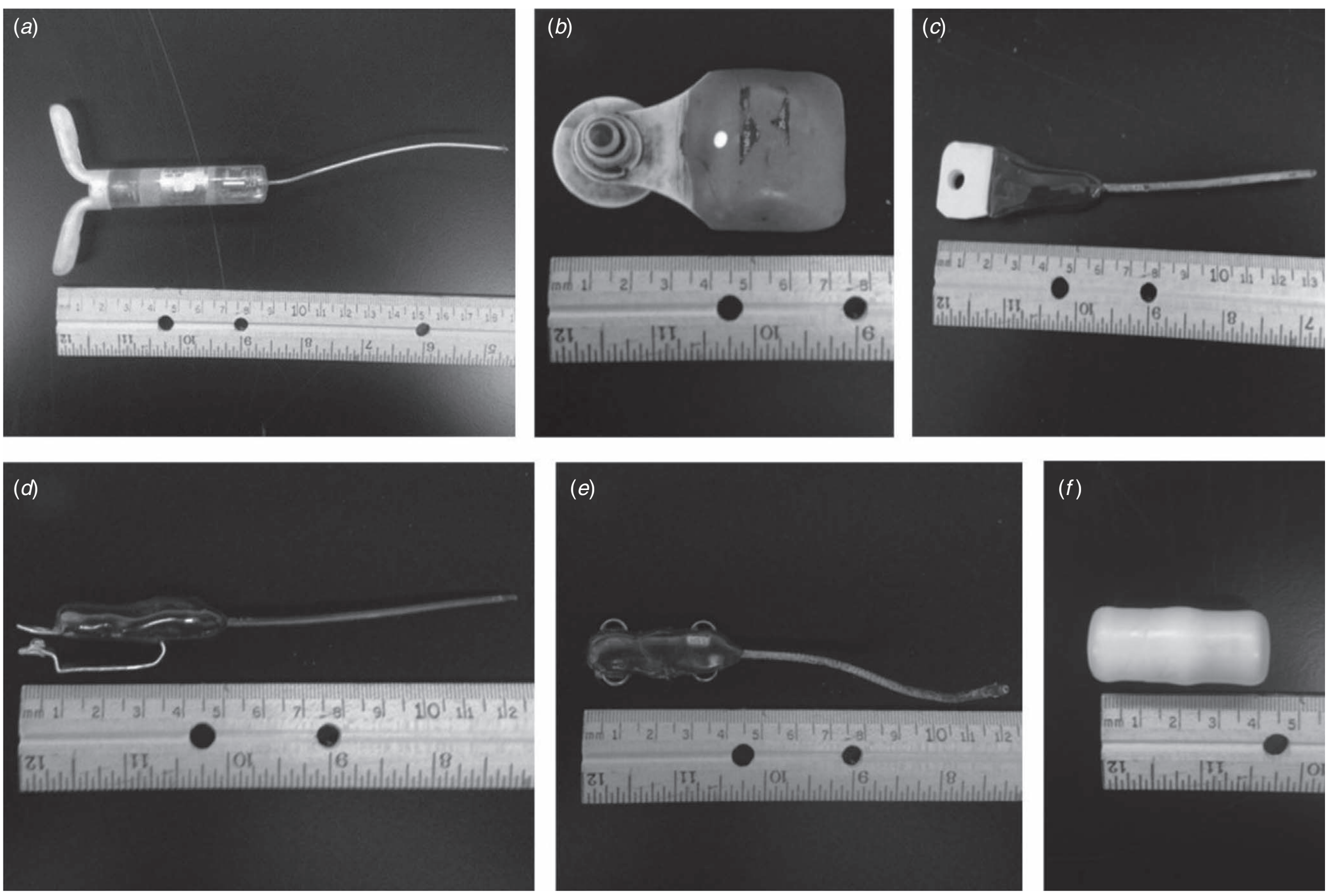

Fig. 1. Tested combinations of transmitters and attachment mechanisms to monitor wild piglet (*Sus scrofa*) survival at the Savannah River Site, South Carolina, USA, 2013–16. The above figure depicts (*a*) a vaginal implant transmitter (VIT), (*b*, *c*) stud ear-tag transmitters, (*d*) side-view of a clip ear-tag transmitter and (*e*) a transmitter with anchor points for suture or harness material attachment, and (*f*) a surgically implantable transmitter.

We tagged piglets captured at the farrowing nest with one of three techniques: sutured and epoxied transmitters, harness transmitters or surgically implanted transmitters (Figs 1, 2). Piglets captured in corral or box traps were tagged with either sutured and epoxied transmitters, surgically implanted transmitters, stud ear-tag transmitters or clip ear-tag transmitters (Figs 1, 2; for sample sizes see below). The transmitters that we attached to piglets via suturing and epoxy (9.0 g), harnesses (9.0 g) and clip ear-tags (8.4 g) were designed by ATS according to our specifications, and incorporated a mortality sensor set to activate following 12 h without movement by the piglet. The surgically implanted transmitters weighed 11.0 g and incorporated a mortality sensor with the same settings (Model IMP100, Telonics, Inc., Mesa, AZ). The transmitters that we attached using the stud ear-tag mechanism were relatively large (20.0 g) and incorporated a mortality sensor set to activate following 4 h without motion from the piglet (Model ZV2E 152, Lotek Wireless, Newmarket, Ontario; Model M3420, ATS). The larger size of this transmitter type allowed incorporation of circuitry that supported a shorter interval mortality sensor. We attached a VHF collar (Model M2520B, ATS) to associated subadult or adult female pigs caught in corral or box traps with piglets to facilitate monitoring of tagged piglets.

Sutured transmitters

Prior to attaching sutured transmitters, we injected piglets with a local analgesic, Lidocaine (2%, MWI Veterinary Supply, ID), at the site of attachment, but did not chemically immobilise the animals. We attached sutured transmitters dorsally, between the scapulae, using dermal surgical sutures through anchor points on the transmitter body (Fig. 1). We also applied a commercially available epoxy (the Gorilla Glue Co., Cincinnati, OH) to the bottom of the transmitter and the site of attachment in an attempt to improve retention time for this transmitter type (Fedak *et al.* 1983). We injected captured piglets with penicillin (dosage: 1 mL 45.3 kg^{-1}; 300 000 units mL^{-1}; Durvet Inc., Blue Springs, MO) before release to decrease risk of infection. A licenced veterinarian trained field personnel in proper suturing techniques and use of analgesics before our implementation of this method.

Harness transmitters

Baubet *et al.* (2009) used harnesses constructed of elastic bands to attach transmitters to wild boar piglets, but found that piglets retained transmitters for only 2.5 days on average. In this study, we constructed harnesses from a Teflon ribbon (Bally Ribbon Mills, Bally, PA), used in the attachment of harnesses to vultures (Holland 2015), that we believed might be more resistant to removal by associated females. We sized these harnesses based upon morphometric measurements of previously captured neonate piglets and sewed a 10-cm band of elastic material on either side of the harness to allow for growth of the piglet. We mounted the radio-transmitter ventrally on the piglet in an additional attempt to make removal of this transmitter type by the associated female less likely (Fig. 2). Chemical immobilisation of captured piglets was not necessary to attach harnesses.

Surgically implanted transmitters

We immobilised captured piglets via intramuscular injection of a combination of Ketamine (10 mg kg^{-1}; MWI Veterinary Supply) and Xylazine (0.5 mg kg^{-1}; MWI Veterinary Supply) and administered Lidocaine via subcutaneous injection at the site of surgery. We sterilised transmitters and surgical tools in Nolvasan Solution (Zoetis Animal Health, Kalamazoo, MI) and used surgical drapes to maximise sterility of field conditions. We created an incision in the abdomen of the immobilised piglet through the dermal layers and muscle tissue using a scalpel, and inserted the sterilised transmitter into the exposed abdominal cavity. For males, we located the incision anterior to the umbilicus and penis, whereas in females the incision was located posterior to the umbilicus. We injected additional Lidocaine directly into the muscle tissue of the abdomen. We closed the incision using one internal layer of surgical sutures through the muscle tissue and employed a second set of internal surgical sutures in the dermis (Fig. 2). We used commercially available cyanoacrylate ('super glue') to further seal the incision, and then injected the piglet with

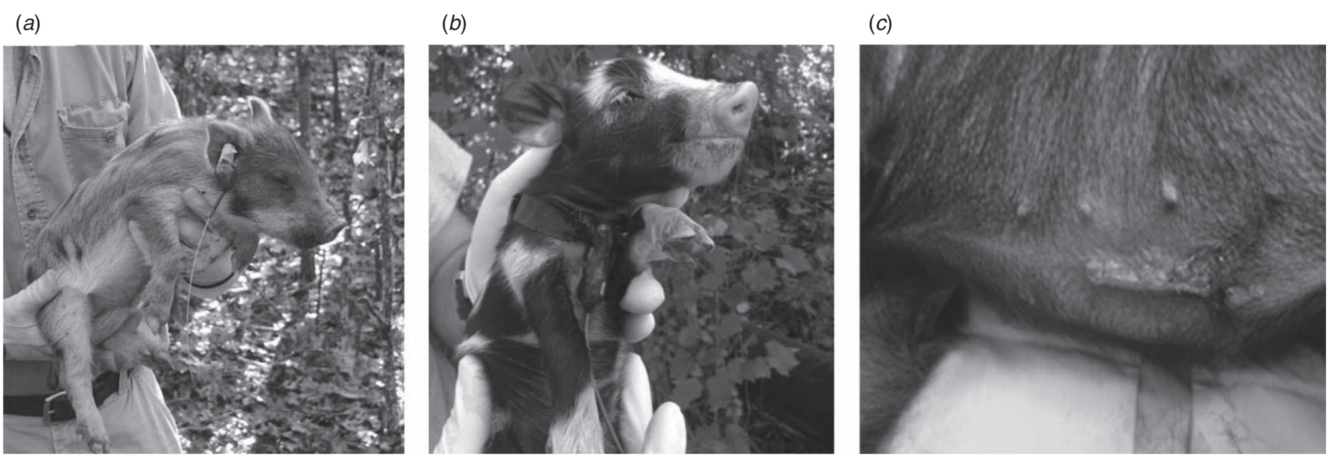

Fig. 2. Selected examples of wild piglets (*Sus scrofa*) tagged with transmitters to monitor survival at the Savannah River Site, South Carolina, USA, 2013–16. Photographs consist of (*a*) a piglet tagged with a stud ear-tag transmitter, (*b*) a piglet tagged with a harness transmitter and (*c*) a transmitter surgically implanted into the abdomen of a piglet.

penicillin to decrease risk of a post-operation infection. Finally, we used an intramuscular injection of Yohimbine (2 mg mL^{-1}; MWI Veterinary Supply) to reverse the chemically immobilised animals. Surgery to implant transmitters into piglets was performed by field personnel trained by a licenced veterinarian.

Stud ear-tag transmitters

During attachment of stud ear-tag transmitters, piglets were chemically immobilised by intramuscular injection using the same dosages of Telazol and Xylazine as above to allow collection of biological samples (e.g. blood, tissue). It should be noted, however, that chemical immobilisation to allow attachment of this transmitter is likely unnecessary, as a similar attachment technique (i.e. stud ear-tag) is approved for use on livestock without chemical immobilisation. The larger size of these transmitters (20 g) precluded their use on piglets weighing less than approximately 3 kg, as the piglet's ear was not large enough to adequately support the transmitter attachment. We used the stud ear-tag mechanism to attach two transmitter body types (Model ZV2E 152 (Lotek Wireless) and Model M3420 (ATS)); we considered these two transmitter types to represent one category due to the fact that they were attached in the same manner and had similar specifications (e.g. weight, pulse rate, battery life, etc.; Fig. 1).

Clip ear-tag transmitters

As with the stud ear-tag transmitters, piglets were chemically immobilised during attachment of clip ear-tag transmitters to allow collection of biological samples, although this may not be necessary for field application under all circumstances. Before attaching this transmitter type, we used a 5-mm biopsy punch to create a hole in the centre of the captured piglet's ear, through which the clip could be threaded.

Monitoring

We located tagged piglets via radio-telemetry 3–7 times for the first week following capture, and 2–4 times weekly thereafter, with the exception of piglets tagged with stud ear-tag transmitters (monitored every 7–10 days). We monitored tagged piglets until mortality of the animal, detachment of the transmitter, hereafter failure, or a minimum of 3 months had passed. When we detected a mortality signal, we homed in on the transmitter and attempted to determine whether the signal was caused by mortality of the piglet or transmitter failure. In each case, we photographed the location of the transmitter and employed a thorough search of a 20-m radius circle surrounding the recovered transmitter for evidence of mortality. If there were no signs of mortality (e.g. carcass, bone fragments, signs of a struggle, bite marks on transmitters, etc.), we assumed that the transmitter attachment mechanism had failed, in order to be conservative in estimating piglet mortality rates. In cases of mortality, we determined the cause of mortality based upon carcass condition, presence of predator tracks, characteristics of cache sites and patterns of piglet carcass consumption (Kilgo *et al*. 2012). We compared average retention times of transmitters, excluding any animals that suffered mortality during the study.

Results

We implanted 14 female pigs with VITs, resulting in the capture of 28 neonate piglets from seven females. Due to the handling time associated with each tagging technique, we did not radio-tag every neonate that we captured (18 of 28 captured piglets were tagged). On three occasions, we experienced failure of the VIT due to its expulsion from the pig before birth of piglets. On three additional occasions, we believe that VIT battery failure or misinterpretation of pregnancy status from ultrasound was responsible for our failure to locate piglets. In one case, we tracked a VIT to a farrowing nest that had been flooded and contained carcasses of piglets. Results of the necropsy of piglets discovered in this nest were inconclusive, but ruled out their death being due to drowning or stillbirth (UGA Veterinary Diagnostic Laboratory, pers. comm.). We found that piglets were relatively mobile at 3 days of age (i.e. able to walk or run) and we recorded one observation of a female and piglets >300 m from the farrowing nest 3 days following parturition. When we approached the farrowing nest, piglets often exhibited a hiding strategy in which they did not move far from the nest ($\leq$5 m), but held still when approached.

We captured, tagged, and monitored 71 piglets using the five combinations of transmitters and attachment mechanisms (Table 1). Of these piglets, 18 were captured by hand at the farrowing nest (25.4%), while 53 were captured in corral or box traps (74.6%). We discuss the cost, advantages, and disadvantages of each combination of transmitter and attachment mechanism in Table 2. We found that stud ear-tag transmitters were retained well by tagged piglets ($\overline{X}$ = 143.0 days, s.e. = 14.05); however, the large size of the transmitter's body precluded their use on true neonates or small-sized individuals (i.e. less than ~3 kg). Sutured transmitters, harness transmitters and clip ear-tag transmitters exhibited poor retention times preventing successful monitoring of piglet survival using these attachment techniques (range of $\overline{X}$ = 2.6–20.6 days; Table 1). Whether the detachment of clip ear-tag and sutured transmitters was due to snagging of the transmitter on vegetation or to behaviour by conspecifics is unknown, but we observed newly tagged piglets chewing and pulling on transmitters attached to other members of the litter. All harness transmitters failed 1–3 days after deployment due to removal of the Teflon straps and/or elastic bands via chewing. We attributed the removal of harnesses to the associated female pig rather than a predator, as there was no evidence of piglet mortality present at the sites where we recovered transmitters,

Table 1. Summary data for performance of each transmitter and attachment mechanism combination tested on juvenile wild pigs (*Sus scrofa*), Savannah River Site, South Carolina, 2013–16

Transmitter[A]	# Tagged (# litters)	# Transmitter failures	Mean transmitter retention (days)	s.e.
Stud ear-tag	23 (6)	3	143.0	14.05
Clip ear-tag	22 (6)	16	20.6	2.31
Sutured and epoxied	10 (3)	10	5.0	1.03
Harness	7 (3)	4	2.6	0.4
Implant	9 (3)	0	98.3	3.25

[A]Indicates the combination of a transmitter unit and attachment mechanism.

Table 2. Practicality of transmitter types for monitoring survival of wild piglets (*Sus scrofa*), Savannah River Site, South Carolina, USA, 2013–2016

Transmitter	Cost (each)	Considerations
Stud ear-tag	\$179.55–\$209.00	• High retention rates • ~5-month warranted battery lifespan • Large size disqualifies use on piglets $\leq$3.0 kg, but miniaturisation may be possible • May not require chemical immobilisation
Clip ear-tag	\$179.55	• Low retention rates • ~8-month warranted battery lifespan • May not require chemical immobilisation
Sutured	\$179.55	• Low retention rates • ~8-month warranted battery lifespan • Requires basic surgical techniques (suturing) in field • Does not require chemical immobilisation
Harness	\$179.55	• Low retention rates • ~8-month warranted battery lifespan • Does not require chemical immobilisation • Requires manufacturing of harnesses
Implant	\$217.00	• High retention rates on piglets $\geq$3 kg • More testing necessary on neonates • ~2-month battery lifespan • Requires chemical immobilisation • Requires performance of surgical techniques in field • May benefit from a holding period to allow recovery of piglets from surgery

and radio-telemetry suggested that harnessed piglets were travelling in company with the female immediately before harness removal. Given the near-immediate failure of all harness and sutured transmitters, we ceased trials of these attachment methods after deployment on four and 10 piglets, respectively. Transmitters that were surgically implanted into piglets of $\geq$3 kg were successfully retained until battery failure occurred, ~3 months following deployment. In one case, an implanted 3-kg piglet suffered mortality within 2 days of release following surgery and was censored from analyses. We are uncertain whether this mortality was related to the surgical procedure. We attempted implantation of radio-transmitters into 2-day old and 3-day old neonates, but following failure of the surgery on two occasions (neonates did not tolerate anaesthesia), discontinued further attempts.

For all transmitter types, excluding mortality within a 2-day censoring period, only three monitored piglets died throughout the study. Eleven tagged piglets of six litters were depredated or died and were scavenged within 2 days of tagging. Although it is not possible to conclusively determine, in six of these cases, we believe that the mortalities resulted from separation of the piglet from the associated female, which may have been prompted by researcher activities. It is possible that in some of these cases separation occurred during the recovery of the tagged piglet from chemical immobilisation. We only observed evidence suggesting researcher-induced abandonment by the female in one litter of piglets captured in a trap; despite being released at the same time as the female, all four tagged piglets were found depredated within 2 days, while the female was found alive within 1 km of the capture location. In addition to instances of observed separation, we encountered one situation in which five neonate piglets in a litter were tagged using harness transmitters and created a large amount of noise during the tagging process; three of these piglets were found depredated the following day, while the other two were determined to be alive and with the mother. Of the 11 observed scavenging or depredation events, caching evidence suggested that coyotes were responsible for the majority (90.1%; Fig. 3), although further study is clearly needed.

Discussion

No successful known-fate survival study of juvenile wild pigs or related wild boar has previously been conducted. This is due to: (1) difficulty in determining parturition date and location to allow tagging of piglets; and (2) the lack of a technique to successfully monitor known fates of piglets. In this study, our use of VITs allowed us to determine, with a high degree of accuracy, when and where parturition by wild pigs took place. We did occasionally experience unsuccessful use of VITs as a result of premature expulsion from the female (21.4%) or misreading of ultrasound results and equipment failures (21.4%), demonstrating that refinement of this technique for wild pigs is necessary. Two refinements we suggest are: (1) additional testing of different size wings on VITs or models of VITs to reduce premature expulsion rates; and (2) procurement and use of equipment to more accurately determine pregnancy status of captured pigs. In addition to allowing the capture of neonates for tagging, VITs offer future avenues of research into the reproductive ecology of this species. Use of VITs (as opposed to the use of traps) to capture piglets may be advantageous in that it is possible to capture, and therefore assess, the survival rates of younger individuals than would be captured in traps (see below). Use

Fig. 3. Depredated wild piglet (*Sus scrofa*) found cached in a manner suggesting that the piglet was killed by a coyote (*Canis latrans*), Savannah River Site, South Carolina, USA, 2015.

of VITs in conjunction with GPS collars or triangulation might allow greater research into the natural history of wild pigs and how movement relates to parturition (Kurz and Marchinton 1972; Baubet *et al*. 2009).

We evaluated five combinations of potential attachment mechanisms and transmitter bodies and found that surgical implantation of a radio-transmitter into the abdominal cavity or attachment of stud ear-tag transmitters can be successfully employed to monitor survival of juvenile wild pigs ($\geq$3 kg). Surgical implantation of transmitters has been employed successfully on other species (e.g. nine-banded armadillos (*Dasypus novemcinctus*); Hernandez *et al*. 2010)), but its use in juvenile wild pigs is novel. We believe the success of this transmitter type is mostly due to the internal placement of the transmitter, which prevents potential loss due to snagging on vegetation or conspecific activity. Use of stud ear-tag transmitters to monitor survival of piglets is, however, likely advantageous over implant transmitters, in that this technique does not require surgery on captured piglets, is less costly and may meet animal welfare requirements without chemical immobilisation. Piglets 2 and 3 days old weighed ~1 kg, meaning that the piglets we tagged with these methods ($\geq$3 kg) were likely a minimum of 1 month old (Barrett 1978). Therefore, further study is required to assess survival of piglets below this size threshold. In addition, miniaturisation of the transmitter body that we attached via the stud ear-tag mechanism may allow monitoring of true neonate piglets.

In contrast to Baubet *et al*. (2009), we did not observe abandonment of any litter of neonates tagged at the farrowing nest (although we did observe evidence of potential abandonment of a litter of piglets tagged in a trap), suggesting that the methods we tested will not result in highly biased estimates of survival as a result of neonate abandonment. However, it is possible that some of the mortalities we observed throughout the study were due to the response of the female pig to researcher activities. Therefore, careful consideration and refinement of tagging and handling techniques is important. We recommend that researchers minimise noise while in the vicinity of the farrowing nest, as excessive noise may attract predators or increase the chance of the female abandoning the litter. Similarly, minimising time spent at the farrowing nest tagging piglets should reduce disturbance and possible olfactory cues that might be picked up by predators. Finally, situations in which piglets are chemically immobilised could potentially predispose them to separation from adults as a result of the physiological effects of recovery.

We observed that piglets experienced high mortality rates when they were separated from the associated female. This implies that the adult pig associated with a litter might be effective at avoiding potential dangers, such as predators, allowing successful recruitment of offspring into the population (Vetter *et al*. 2016), and therefore, mortality of the female might also result in mortality of the offspring under certain circumstances. Adoption of 'orphaned' litter members by other female wild pigs or attainment of a threshold body size could reduce losses caused by abandonment or mortality of the mother, but more research is required to assess survival rates of orphaned or abandoned piglets and the frequency of adoption events. Additional research is also necessary to determine if independence exists in survival probabilities of piglets from the same litter. Our data suggest that, at least in cases of female abandonment, multiple members of the litter are likely to suffer mortality, suggesting non-independence of fates. In captive conditions, personality traits of female wild boar influence litter survival in the absence of predators (Vetter *et al*. 2016), and additional studies might investigate the influence of the mother's age, total litter size and environmental conditions on the survival of neonate wild pigs.

Previous research reported crushing, conspecific aggression, depredation, exposure and starvation as causes of death in wild piglets (Barrett 1978; Baubet *et al*. 2009). Although evidence suggested that the majority of mortality events we observed were depredation events, piglets in our study area are undoubtedly affected by these causes as well. Our discovery of non-stillborn, dead, 2-day old piglets in a farrowing nest confirms this, despite the fact that cause of death was not conclusively determined. The discovery of these piglets also further highlights the need to monitor piglet survival as soon as feasible following birth, in order to obtain the best possible data on survival rates for use in modelling of population dynamics. Further development of attachment techniques to allow their use on true neonate animals is, therefore, necessary.

Conclusions

Use of effectively retained stud ear-tag transmitters or surgically implanted transmitters will allow future studies to determine cause-specific mortality in wild piglets and evaluate the effects of environmental and demographic factors on mortality rates, thereby facilitating refinement of population models for this abundant invasive species. Use of VITs to determine litter sizes and allow tagging of neonates will also allow improvement in estimates of demographic rates in wild pigs. Our preliminary monitoring results suggest piglets may experience relatively low natural mortality rates, necessitating more effective lethal control of this age class to prevent population growth. Work by Bieber and Ruf (2005) and Mellish *et al*. (2014) suggested the importance of management actions affecting juvenile pigs, but was largely unsupported by estimates of known-fate survival. Until an attachment technique is developed for true neonate piglets, use of VITs to count piglets immediately after parturition, in conjunction with subsequent monitoring, may allow coarse estimation of survival rates for piglets until they attain a size sufficient to allow tagging.

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References

Aldridge, H. D. J. N., and Brigham, R. M. (1988). Load carrying and maneuverability in an insectivorous bat: a test of the 5% rule of radio-telemetry. *Journal of Mammalogy* **69**, 379–382. doi:10.2307/1381393

Barrett, R. H. (1978). Feral hog at Dye Creek Ranch, California. *Hilgardia* **46**, 283–355. doi:10.3733/hilg.v46n09p283

Barrios-Garcia, M. N., and Ballari, S. A. (2012). Impact of wild boar (*Sus scrofa*) in its introduced and native range: a review. *Biological Invasions* **14**, 2283–2300. doi:10.1007/s10530-012-0229-6

Baubet, E., Servanty, S., and Brandt, S. (2009). Tagging piglets at the farrowing nest in the wild: some preliminary guidelines. *Acta Silvatica & Lignaria Hungarica* **5**, 159–166.

Beasley, J. C., Grazia, T. E., Johns, P. E., and Mayer, J. J. (2013). Habitats associated with vehicle collisions with wild pigs. *Wildlife Research* **40**, 654–660. doi:10.1071/WR13061

Bengsen, A. J., Gentle, M. N., Mitchell, J. L., Pearson, H. E., and Saunders, G. R. (2014). Impacts and management of wild pigs *Sus scrofa* in Australia. *Mammal Review* **44**, 135–147. doi:10.1111/mam.12011

Bevins, S. N., Pedersen, K., Lutman, M. W., Gidlewski, T., and Deliberto, T. J. (2014). Consequences associated with the recent range expansions of nonnative feral swine. *Bioscience* **64**, 291–299. doi:10.1093/biosci/biu015

Bieber, C., and Ruf, T. (2005). Population dynamics in wild boar *Sus scrofa*: ecology, elasticity of growth rate and implications for the management of pulsed resource consumers. *Journal of Applied Ecology* **42**, 1203–1213. doi:10.1111/j.1365-2664.2005.01094.x

Bishop, C. J., Anderson, C. R. Jr, Walsh, D. P., Bergman, E. J., Kuechle, P., and Roth, J. (2011). Effectiveness of a redesigned vaginal implant transmitter in mule deer. *The Journal of Wildlife Management* **75**, 1797–1806. doi:10.1002/jwmg.229

Campbell, T. A., and Long, D. B. (2009). Feral swine damage and damage management in forested ecosystems. *Forest Ecology and Management* **257**, 2319–2326. doi:10.1016/j.foreco.2009.03.036

Diefenbach, D. R., Kochanny, C. O., Vreeland, J. K., and Wallingford, B. D. (2003). Evaluation of an expandable breakaway radiocollar for white-tailed deer fawns. *Wildlife Society Bulletin* **31**, 756–761.

Dreitz, V. J., Baeten, L. A., Davis, T., and Riordan, M. M. (2011). Testing radiotransmitter attachment techniques on northern bobwhite and chukar chicks. *Wildlife Society Bulletin* **35**, 475–480. doi:10.1002/wsb.73

Fedak, M. A., Anderson, S. S., and Curry, M. G. (1983). Attachment of a radio tag to the fur of seals. *Journal of Zoology* **200**, 298–300. doi:10.1111/j.1469-7998.1983.tb05794.x

Gaines, K. F., Porter, D. E., Punshon, T., and Brisbin, I. L. Jr (2005). A spatially explicit model of the wild hog for ecological risk assessment activities at the Department of Energy's Savannah River Site. *Human and Ecological Risk Assessment* **11**, 567–589. doi:10.1080/10807030590949654

Gortázar, C., Acevedo, P., Ruiz-Fons, F., and Vicente, J. (2006). Disease risks and overabundance of game species. *European Journal of Wildlife Research* **52**, 81–87. doi:10.1007/s10344-005-0022-2

Hanson, L. B., Mitchell, M. S., Grand, J. B., Jolley, D. B., Sparklin, B. D., and Ditchkoff, S. S. (2009). Effect of experimental manipulation on survival and recruitment of feral pigs. *Wildlife Research* **36**, 185–191. doi:10.1071/WR08077

Hayes, R., Riffell, S., Minnis, R., and Holder, B. (2009). Survival and habitat use of feral hogs in Mississippi. *Southeastern Naturalist* **8**, 411–426. doi:10.1656/058.008.0304

Hernandez, S. M., Gammons, D. J., Gottdenker, N., Mengak, M. T., Conner, L. M., and Divers, S. J. (2010). Technique, safety, and efficacy of intra-abdominal transmitters in nine-banded armadillos. *The Journal of Wildlife Management* **74**, 174–180. doi:10.2193/2008-502

Holland, A. E. (2015). Spatial ecology of black and turkey vultures in the southeastern United States. M.Sc. Thesis. University of Georgia, Athens, GA.

Hubbard, M. W., Tsao, L.-L. C., Klaas, E. E., Kaiser, M., and Jackson, D. H. (1998). Evaluation of transmitter attachment techniques on growth of wild turkey poults. *The Journal of Wildlife Management* **62**, 1574–1578. doi:10.2307/3802024

Imm, D. W., and McLeod, K. W. (2005). Plant Communities. In 'Ecology and Management of a Forested Landscape: Fifty Years on the Savannah River Site'. (Eds J. C. Kilgo and J. I. Blake.) pp. 106–161. (Island Press: Washington, DC.)

Keiter, D. A., and Beasley, J. C. (2017). Hog heaven? Challenges of managing wild pigs in natural areas. *Natural Areas Journal* **37**, 6–16. doi:10.3375/043.037.0117

Keuling, O., Lauterbach, K., Stier, N., and Roth, M. (2010). Hunter feedback of individually marked wild boar *Sus scrofa* L.: dispersal and efficiency of hunting in northeastern Germany. *European Journal of Wildlife Research* **56**, 159–167. doi:10.1007/s10344-009-0296-x

Keuling, O., Baubet, E., Duscher, A., Ebert, C., Fischer, C., Monaco, A., Podgórski, T., Prevot, C., Ronnenberg, K., Sodeikat, G., Stier, N., and Thurfjell, H. (2013). Mortality rates of wild boar *Sus scrofa* L. in central Europe. *European Journal of Wildlife Research* **59**, 805–814. doi:10.1007/s10344-013-0733-8

Kilgo, J. C., Ray, H. S., Vukovich, M., Goode, M. J., and Ruth, C. (2012). Predation by coyotes on white-tailed deer neonates in South Carolina. *The Journal of Wildlife Management* **76**, 1420–1430. doi:10.1002/jwmg.393

Krull, C. R., Stanley, M. C., Burns, B. R., Choquenot, D., and Etherington, T. R. (2016). Reducing wildlife damage with cost-effective management programs. *PLoS One* **11**, e0146765. doi:10.1371/journal.pone.0146765

Kurz, J. C., and Marchinton, R. L. (1972). Radiotelemetry studies of feral hogs in South Carolina. *The Journal of Wildlife Management* **36**, 1240–1248. doi:10.2307/3799254

Mayer, J. J. (2002*a*). A simple field technique for age determination of adult wild pigs: environmental information document. Westinghouse Savannah River Company WSRC-RP-2002–00635, Westinghouse Savannah River Company, Aiken, SC.

Mayer, J. J., and Brisbin, I. L. Jr (Eds) (2008). 'Wild pigs in the United States: Their History, Comparative Morphology, and Current Status.' (University of Georgia Press: Athens, GA.)

Mayer, J. J., Martin, F. D., and Brisbin, I. L. Jr (2002*b*). Characteristics of wild pig farrowing nests and beds in the upper Coastal Plain of South Carolina. *Applied Animal Behaviour Science* **78**, 1–17. doi:10.1016/S0168-1591(02)00114-4

Mellish, J. M., Sumrall, A., Campbell, T. A., Collier, B. A., Neill, W. H., Higginbotham, B., and Lopez, R. R. (2014). Simulating potential population growth of wild pig, *Sus scrofa*, in Texas. *Southeastern Naturalist (Steuben, ME)* **13**, 367–376. doi:10.1656/058.013.0217

Sáenz-de-Santa-María, A., and Tellería, J. L. (2015). Wildlife–vehicle collisions in Spain. *European Journal of Wildlife Research* **61**, 399–406. doi:10.1007/s10344-015-0907-7

Servanty, S., Gaillard, J.-M., Ronchi, F., Focardi, S., Baubet, E., and Gimenez, O. (2011). Influence of harvesting pressure on demographic tactics: implications for wildlife management. *Journal of Applied Ecology* **48**, 835–843. doi:10.1111/j.1365-2664.2011.02017.x

Taylor, R. B., Hellgren, E. C., Gabor, T. M., and Ilse, L. M. (1998). Reproduction of feral pigs in southern Texas. *Journal of Mammalogy* **79**, 1325–1331. doi:10.2307/1383024

Toïgo, C., Servanty, S., Gaillard, J.-M., Brandt, S., and Baubet, E. (2008). Disentangling natural from hunting mortality in an intensively hunted wild boar population. *The Journal of Wildlife Management* **72**, 1532–1539.

Vetter, S. G., Brandstätter, C., Macheiner, M., Suchentrunk, F., Gerritsmann, H., and Bieber, C. (2016). Shy is sometimes better: personality and juvenile body mass affect adult reproductive success in wild boars, *Sus scrofa*. *Animal Behaviour* **115**, 193–205. doi:10.1016/j.anbehav.2016.03.026

Warner, R. E., and Etter, S. L. (1983). Reproduction and survival of radio-marked hen ring-necked pheasants in Illinois. *The Journal of Wildlife Management* **47**, 369–375. doi:10.2307/3808509

Williams, B. L., Holtfreter, R. W., Ditchkoff, S. S., and Grand, J. B. (2011). Trap style influences wild pig behavior and trapping success. *The Journal of Wildlife Management* **75**, 432–436. doi:10.1002/jwmg.64