9 Research Methods for Wild Pigs

James C. Beasley, Michael J. Lavelle, David A. Keiter, Kim M. Pepin, John C. Kilgo, and Kurt C. VerCauteren

CONTENTS

9.1 INTRODUCTION

Many aspects of *Sus scrofa* biology are well described as pigs have been domesticated for nearly 10,000 years (see Chapter 2), serving as food for humans and model organisms routinely used as human surrogates in medical and forensic sciences (Swanson et al. 2004, Dekeirsschieter et al. 2009). Aspects of domestic pig biology that are well understood include their physiology, aging, genetics, and reproduction. In particular, the entire *Sus scrofa* genome was sequenced in 2012, resulting in substantial understanding of the genetic architecture and traits in this species. Despite our knowledge of domestic pigs, basic biological and ecological attributes of wild *Sus scrofa* remain understudied, particularly in their invasive ranges. Such deficiencies stem from a multitude of factors, historically reflecting a lack of interest and funding for basic ecological studies, with almost no research published on wild pigs prior to the 1950's (Figure 9.1). However, a dramatic increase in ecological studies on *Sus scrofa* has occurred over the last few decades, within both its native and invasive ranges (Figure 9.1). In North America, this increase reflects growing awareness of economic and ecological impacts that wild pigs have on both native and anthropogenic ecosystems (e.g., agriculture).

Although there is growing interest in research on wild pigs, a number of challenges exist to studying basic aspects of their ecology and management due to their social structure, physiology, and adaptability. For example, wild pigs exhibit a complex social structure, yet observational study methods commonly used to elucidate behavior and social dynamics of other social species like primates and elephants are often not feasible with wild pigs because of their secretive behavior. Similarly, while advancements in telemetry technology have revolutionized our knowledge of spatial ecology for many species, issues with rapid weight gain and body structure in wild pigs have limited the application of these technologies. However, researchers have addressed some of these issues and telemetry studies are becoming more common (e.g., Pepin et al. 2016, Kay et al. 2017). Likewise, despite its importance for modeling pig population dynamics, no studies have successfully quantified known-fate survival of neonate wild pigs, primarily because tools to conduct such assessments are limiting (Keiter et al. 2017a).

Adding to challenges associated with studying wild pigs, as a heavily persecuted and in some instances regulated invasive species, research goals may be at odds with management objectives. For example, releasing captured wild pigs for ecological study may be politically unacceptable in some cases. Furthermore, there are now few landscapes where wild pigs are unmanaged, limiting

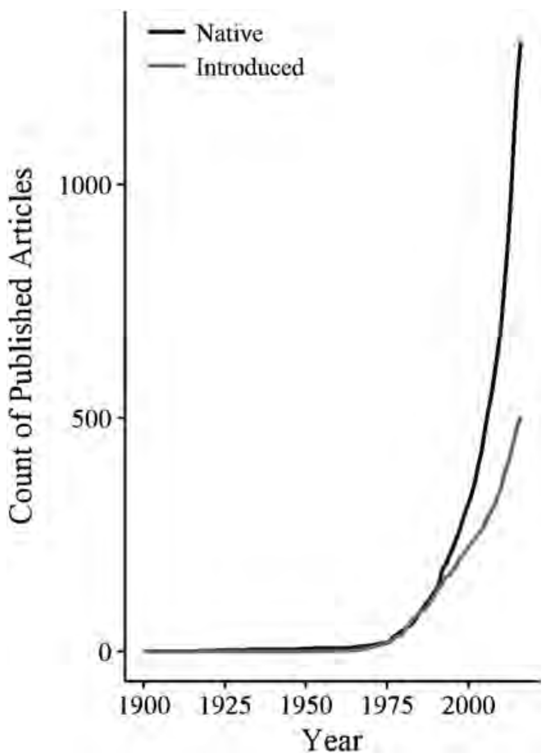

FIGURE 9.1 Counts of published articles on wild pigs within their introduced and native ranges from 1910 to November 2016. (Adapted from Web of Science; Search terms: feral pigs, feral swine, *Sus scrofa*, wild boar, wild hogs, wild pigs.)

inferences about complex aspects of pig ecology (e.g., social structure) in the absence of anthropogenic activity and how management may influence pig behavior and population dynamics. These types of data are essential to development of effective strategies for controlling this important invasive species. Wild pigs also are secretive and intelligent, and as a result can be difficult to study in areas with abundant cover and heavy management pressure.

In this chapter we highlight the current state of research tools, emphasizing advancements in technologies and methodologies used to study wild pig ecology, management, and damage assessment. While much of the chapter focuses on research in North America (invasive range), these technologies and methods are applied globally to study wild pigs. As such, we have incorporated representative literature from throughout the native and invasive ranges of this species. Topics vary from highly applied field methods such as trapping, handling, and monitoring techniques, to lab-based assessments of molecular ecology, disease, and diet, highlighting analysis techniques of these types of data where appropriate. We also include methodology associated with pig population control and damage assessment. We conclude by summarizing the current state of knowledge of wild pig ecology, pointing to future research tools and methods, and emphasizing data gaps to guide future research.

9.2 CAPTURE AND HANDLING

Capturing wild pigs for research is considerably different from capture for population control. Capture techniques vary widely and should be tailored to intended research or management outcomes. For example, if capture is for collection of biological samples for disease surveillance across all sexes and age classes, aerial gunning (if lethal sampling is acceptable) or multiple animal capture with drop nets or corral traps may be the most appropriate strategies. Conversely, if specific genders or age classes are targeted, remotely monitored and activated traps may be most valuable. Trapping is the most widely used method for live capturing wild pigs. A variety of effective traps exist, with semi-permanent corral traps and portable rigid-wire box traps being the most common (e.g., Keiter and Beasley 2017; Figure 9.2). Although corral traps require more time to construct than placement of a box trap, the benefit is that quantity of pigs captured per unit effort is typically higher. In the United States and elsewhere, commercially produced traps and gates may be available locally at farm-supply stores, can be found through Internet searches, or can be hand built (Long and Campbell 2012). In general, trap configurations are relatively consistent, yet there are an array of gate designs, trigger types, and trap configurations (Long and Campbell 2012, Metcalf et al. 2014).

9.2.1 Trap Gates

There are 2 basic types of gates most commonly used for trapping wild pigs, single-catch gates that remain closed once triggered (e.g., guillotine) and continuous-catch gates (e.g., rooter, saloon) that are intended to allow additional captures once the gate is shut (Figure 9.3). Although continuous-catch doors have potential to increase capture success, there is also increased potential for escape due to intentional lack of resistance to reopen gates. Some research has found continuous-catch gates to be ineffective at increasing number of pigs captured (Smith et al. 2014). Additionally, Long and Campbell (2012) reported that capture rates of adults did not vary between box traps with side-swing or rooter gates (Figure 9.3), but rooter gates caught more juveniles. In contrast, guillotine-style gates (Figure 9.3) provide unobstructed entry into a trap and, once triggered, escape is less common. Many trappers recommend using 2 synchronized guillotine gates on opposite sides of a corral trap to decrease reluctance of wary pigs to enter traps.

Gate designs are shifting away from narrow (0.9–1.2-m wide) side-hinged styles to larger (e.g., 2.4-m-wide) overhead guillotine-style gates, although there is limited evidence to suggest a marked increase in trapping efficacy (Metcalf et al. 2014; Figure 9.3). In some circumstances, a variety of overhead capture devices including drop corral traps, drop nets, and net cannons or projectors that

FIGURE 9.2 Proven devices for capture of wild pigs. (a) Corral traps are commonly used, while (b) air cannons with netting and (c) drop nets can also be effective. (d) Recently developed drop traps can be very effective by suspending the entire trap overhead, thus minimizing impediments to entering traps. Corral traps are typically triggered by pigs when a trip wire is contacted or by remote activation and monitoring through cameras and cell phones (e.g., (a) and (d) have become increasingly popular). Remote-activated systems are highly effective (pending remote signal coverage and strength), and can help minimize non-target captures. Drop nets and air cannon nets do not require animals to enter an enclosure and thus may improve efficacy when used on trap-wary animals and for capturing specific individuals. (Photos (a–c) by the USDA/APHIS/WS/National Wildlife Research Center and (d) by J. Beasley. With permission.)

fire nets over wild pigs are useful alternatives (Figure 9.2), especially for those pigs reluctant to enter more traditional cage traps (Gaskamp 2012, Bauman 2015).

Gates can be adapted for any trapping scenario (Figure 9.3). For example, remote, user-activated gate options are commercially available and include systems that incorporate cameras that enable remote identification of animals entering traps and trap activation via smart phone. These designs can be particularly useful when trying to capture specific individuals or for maximizing the proportion of a group captured. Such technology has revolutionized trapping by increasing efficiency and minimizing wasted effort associated with non-target captures. Current drawbacks are recurring costs (e.g., cellular data plans) and reliance on cellular or satellite coverage, although most of these traps can be adapted to be triggered manually via trip lines or root sticks if necessary.

9.2.2 Trap Triggers

Trap triggers typically include a gate retention mechanism that is released when a trip line is pulled. The trip line typically runs horizontally near the back of the trap, at a height that target animals will need to push through, that is linked to the gate retention mechanism. Bait is deposited behind and below the trip line so that animals will inadvertently apply pressure to it while feeding and release the gate. Another frequently used trigger mechanism is a "root stick," which is essentially a stick acting as a temporary anchor for the trip line. The stick is secured horizontally to the ground by 2 more set sticks inserted into the ground at an angle away from the direction of pull. Bait is then dispersed around the entire root stick setup; the root stick then becomes dislodged by pigs during feeding, releasing the gate. Sailing snap shackles and spring-loaded locking pliers are ideal

FIGURE 9.3 Trap gate styles commonly used for capturing wild pigs. (a, f) Single-catch, guillotine-style gates rely on gravity to keep the gate closed, although some traps include mechanisms (like stops) that prohibit raising the gate without first releasing the mechanism. (b–e) Continuous-catch gates allow additional pigs to enter the trap after the gate has been triggered and closed. Gate (f) is an example of an increasingly popular design that incorporates remote monitoring and activation by cell phone and can be triggered as desired when an operator identifies target animals in the trap. (Photos (a) by the National Feral Swine Damage Management Program and (b–f) by the USDA/APHIS/WS/National Wildlife Research Center. With permission.)

triggering mechanisms to secure cables holding the gate open until the trip line is activated by pigs (Figure 9.4).

9.2.3 Bait

Bait used for trapping typically includes dry or fermented whole kernel corn or wheat, which performs reliably, is relatively inexpensive, and is widely accessible. Numerous alternative baits and attractants have been evaluated for attracting wild pigs (e.g., Wathen et al. 1988, Campbell and Long 2008, Williams et al. 2011), although assessment of the best bait types for any specific location or season is highly recommended. Be sure to check state game laws on baiting, as some states restrict the types, amounts, and locations of baits that can be used without special permission. Alternative baits including meat, berry flavoring, and livestock feed additives have been successful, although results are highly variable (Wathen et al. 1988, Campbell and Long 2009a). Research has yet to identify any baits specific to wild pigs (Lavelle et al. 2017, Beasley et al. 2018). Availability of natural foods during capture efforts undoubtedly influences motivation of target animals to respond to bait, and thus impacts trapping productivity (Williams et al. 2011, Long and Campbell 2012).

9.2.4 Other Capture Methods

Capture using dogs trained to locate, pursue, catch, and restrain wild pigs is a possibility given the right circumstances, including widespread landowner permission. Use of dogs is often more applicable to lethal control of wild pigs when indiscriminate captures are acceptable (Bauman 2015). Further, the outcome can be unpredictable and physically demanding on all parties involved, and efforts may prove counterproductive to other ongoing capture efforts from displacement of target pigs (Bauman 2015).

FIGURE 9.4 Manual trigger mechanisms for activating gates on traps for capturing wild pigs including: (a) sailing shackle and steel ring, (b) root stick, and (c) locking pliers and steel ring. Triggers (a) and (c) are activated when a wild pig applies force to a trip wire attached to the mechanism causing the ring attached to the gate to be released. Trigger (b) is activated as a wild pig consumes bait around the mechanism and dislodges any of the sticks that are acting as an anchor and holding the gate open. (Photos by the USDA/APHIS/WS/National Wildlife Research Center. With permission.)

Aerial gunning from helicopters or fixed-wing aircraft can be highly productive relative to other capture methods for acquiring a large number of samples from dead pigs in a short period of time (Saunders 1993, Campbell et al. 2010). To relocate animals after aerial gunning, paper streamers and global positioning system (GPS) waypoints can be helpful for directing ground crews. Shooting animals over bait can also be effective for collecting specific individuals. Strategically placed tree stands, considering prevailing winds, and night vision or thermal optics will improve efficiency of this technique.

The aforementioned methods lend themselves to research requiring capture and release or lethal sampling. Selection of capture method(s) should include thorough consideration of available resources including labor, traps, bait, and funds, as wild pig capture typically requires significant investments. Further, capture objectives such as number of animals, targeted age class, sex, size, and spatial distribution help determine which capture strategies will be most productive and efficient to implement (Mayer 2009).

9.2.5 Handling

An important consideration when capturing wild pigs for research that will be released is ensuring they are released uninjured. A drawback of all previously mentioned capture tools (except nets) is that they are constructed of seemingly permeable, though rigid wire that has the potential to cause injury (Barasona et al. 2013, Casas-Díaz et al. 2015). To reduce damage-inflicting stimuli from outside the trap and minimize stress of captured animals, traps should be approached quietly and slowly, or shade cloth can be used to enshroud an entire trap after animals are captured (Sweitzer et al. 1997, Fowler 2011). As the shade cloth is put in place, an instant calming effect is observed with a reduction in attempted jumps and impacts with corral panels (Lavelle et al. 2019). Further, not only do pigs calm down, but they also stand still, improving the chances for a successfully placed immobilization dart or injection.

Chemical immobilization strategies for wild pigs are straightforward, although considerable variability in individual responses to drugs is common (Calle and Morris 1999). Delivery of anesthetics is typically accomplished by injection with darts or pole syringes. When anesthetizing pigs at close range (<2 m) in box traps or in nets, blow guns, or pole syringes are ideal for delivery, whereas dart guns are ideal for larger traps. Once injected, induction rates depend on drug choice, injection site, level of excitement of animals, and completeness of injection (Calle and Morris 1999). Due to the presence of fat deposits, especially on the dorsal aspect of the rump, a long needle (>3.0 cm) for intramuscular injections is required (Fowler 2011), but needle length should be adjusted for pig size. To penetrate tough outer hide and layers of fat, needles should be sturdy (e.g., 14 or 16 gauge). A combination of Telazol® (4.4 mg/kg) and xylazine (2.2 mg/kg) is commonly used to anesthetize pigs (Fenati et al. 2008, Heinonen et al. 2009). However, variability in responses among individuals has been observed with some animals exhibiting compromised thermoregulation or prolonged immobilization (Calle and Morris 1999). These variations potentially stem from variability in the quality of injections (e.g., injection location, deep fat deposits, environmental conditions affecting metabolism). This unpredictability has led to exploration of novel combinations such as ketamine/medetomidine, midazolam/detomadine/butorphanol, medetomidine/midazolam/butorphanol, butorphanol/azaperone/medetomidine, and nalbuphine/medetomidine/azaperone (Heinonen et al. 2009, Kreeger and Arnemo 2012, Ellis et al. 2019).

Although challenging, it is possible to anesthetize wild pigs with dart projectors from a blind. If darting is used for capture, we recommend use of telemetry-equipped transmitter darts to improve the likelihood of locating anesthetized animals (Walter et al. 2005, Thurfjell et al. 2009). A pig will likely travel 200–300 m into thick underbrush after darted, making recovery difficult even with transmitter darts (Thurfjell et al. 2009). One particular benefit of darting is targeting of specific individuals (e.g., for replacing batteries in collars or taking biological samples from an individual over time), although researchers should be aware darting of specific pigs can require considerable effort and is not always successful. Aerial net gunning has also been used to capture wild pigs (R. K. Brook, College of Agriculture and Bioresources, University of Saskatchewan, and D. E. Etter, Michigan Department of Natural Resources, unpublished data).

Physical handling and restraint of captured wild pigs also is possible. If traps are located near roads and are constructed with a gate or loading port to insert a chute, it is possible to move pigs from traps to a handling device or trailer for processing (Figure 9.5). Commercially available squeeze chutes designed for small livestock can be useful in restraining wild pigs (Fowler 2011). Elaborate custom-fabricated mobile handling trailers are also a possibility for extensive handling (Lavelle et al. In Review; Figure 9.5). As wild pigs are powerful and aggressive, utmost care in handling is needed.

9.3 MONITORING TECHNIQUES

Development of techniques to monitor wild pig populations and effects on the environment has recently increased. Knowledge of population density and demographic rates, such as survival and reproduction, as well as changes in these rates, is critical to understanding wild pig ecology and improving management programs that minimize impacts on natural and anthropogenic ecosystems. Here we discuss the development of methods to collect and assess these demographic data.

9.3.1 Marking and Tracking Techniques

Research on assessing vital rates, spatial ecology, and habitat use often involve marking wild pigs with devices ranging from individually identifiable ear tags to GPS transmitters. However, wild

FIGURE 9.5 Devices adapted or designed to facilitate handling captured wild pigs. (a, d) Squeeze chutes can be moved from a transport trailer into place after capturing wild pigs. (b, c) Custom-fabricated trailers incorporate multiple holding areas and handling stalls, and can be designed to connect to traps following capture. (Photos (a) by J. Suckow, (b) by the Range Cattle Research and Education Center - University of Florida, (c) by the USDA/APHIS/WS/National Wildlife Research Center, and (d) by R. Powers. With permission.)

pigs pose a number of behavioral and physiological challenges to many commonly used methods of tagging and tracking. For example, individual identification via direct or camera observation of tag or collar numbers is frequently hindered by mud from wallowing behavior. Additionally, fighting, particularly between males, can result in loss of external tags. Wild pigs have also been individually marked with passive integrated transponders (PIT) tags, which are relatively inexpensive and allow quantification of individual visits to sites containing monitoring stations, if the marked pigs can be coerced into passing within range of the monitoring station (Campbell et al. 2013a).

Very high frequency (VHF) or GPS transmitters are often used to monitor wild pig spatial ecology, habitat use, and survival. Recently, research has highlighted the need for more information on inter- and intraspecific contact rates to improve assessments of disease transmission risk by wild pigs (Pepin et al. 2016). Proximity collars, which incorporate a sensor that records contacts between collared animals at a discrete distance, provide one method to help address this knowledge gap. A challenge is that the electronic components of GPS transmitters can be damaged through rough treatment by wild pigs (e.g., rooting and wallowing). As such, researchers should temper their expectations of transmitter longevity and manufacturers should improve transmitter designs to withstand wear. For example, rooting behavior places considerable stress on component housings that hang from the neck and thus component housings on these types of collars require structural reinforcement.

When using GPS transmitters, determination of an appropriate fix schedule will depend on project objectives. For example, wild pigs tend to be less active during daylight hours in some seasons and locations (see Chapter 3), hence it may be possible to prolong battery use and minimize data upload costs by reducing fixes during the day.

Methods to attach VHF and GPS transmitters to wild pigs differ for adult and juvenile animals. Like many ungulates, VHF and GPS transmitters are often attached to pigs via neck collars. However, due to the circumference of the neck relative to the head, combined with the propensity of wild pigs to rub on trees and posts, collars generally must be fitted tighter than for other species or they will slip off the animal within a few weeks. Further compounding the problem of collar retention, pig body size and weight can fluctuate dramatically among seasons, resulting either in the collar becoming too loose (and falling off the animal prematurely) or too tight (creating animal welfare concerns). We recommend considering sex and approximate age of the animal, as well as season into account prior to attaching neck collars. Researchers also must judge whether the animal is likely to experience high weight gain or loss (e.g., due to pregnancy status), and this can vary by location. We also recommend complementing telemetry with targeted camera trapping to monitor animal welfare after collaring.

Harness transmitter attachments (see Chapter 14) encounter similar issues often to a greater degree, but were successfully employed by Fischer et al. (2016) on adult pigs for relatively short time frames (≤3 months). Researchers in Michigan also fit a GPS collar and harness to an adult female for 293 days with no visible signs of significant physical or locomotory stress. This animal had pronounced wild boar morphology and undoubtedly changed weight during this time, but perhaps not to the extent observed in southern wild pigs of more domestic origin. Ear tag transmitters on adult wild pigs are less commonly used, but may be appropriate when project goals do not require extended battery life or frequent upload of GPS points (Keuling et al. 2010).

Use of neck collars on juveniles is generally infeasible due to rapid growth and issues with neck conformation and behaviors similar to adults. Harness transmitters have been used unsuccessfully on piglets (Baubet et al. 2009, Keiter et al. 2017a), failing because of removal of transmitters by conspecifics, most likely the associated sow. Surgical implantation of VHF transmitters into the abdominal cavity of piglets has also been used with mixed efficacy, being more successful on piglets >3 kg (Keiter et al. 2017a). Ear tag transmitters may be the most effective technique currently available to monitor juvenile wild pigs, as ear tags do not require field surgery for attachment, and are typically retained on piglets >3 kg (Keiter et al. 2017a). Ear tag transmitters designed for neonate (<3-kg) pigs have been successfully deployed on wild pigs 1–2 days old, although retention times appear to be limited to several weeks (S. Chinn, Warnell School of Forestry and Natural Resources, University of Georgia, unpublished data). Further miniaturization of VHF and GPS transmitters will likely facilitate improved monitoring of piglets in the future.

9.3.2 Aging

Knowing the age of individual wild pigs can be important for many research and population assessment purposes. Cementum annuli in molariform teeth can be used to age wild pigs, but uncertainty remains as to the age and frequency at which annular rings develop in different climates and habitats (Clarke et al. 1992, Choquenot and Saunders 1993). Patterns of premolar and molar eruption can be used to assign wild pigs to age classes: piglet (0–0.5 years); juvenile (0.5–1 years); yearling (1–1.5 years); subadult (1.5–3 years); and adult (>3 years) (Mayer and Brisbin 2008). Furthermore, Halseth et al. (2018) developed a wild pig aging guide using tooth eruption and replacement with age classes categorized as 0–8 weeks, 8–20 weeks, 20–30 weeks, 30–51 weeks, 12–18 months, 18–26 months, 26–36 months, 36–48 months, and 48+ months. In addition, Mayer (2002) presented a method for using tooth wear, i.e., relative exposure of dentine on molars, to estimate ages >3 years, but criteria for assigning age likely differ by geographic location.

9.3.3 Reproduction

As with other mammals, productivity can be assessed by direct observation and examination of reproductive organs. Male reproductive condition has been determined using presence of spermatozoa and testicular measurements, including mass and volume (e.g., Sweeney et al. 1979, Johnson et al. 1982). Examination of female reproductive tracts can yield counts of corpora lutea and fetuses, which provide information on ovulation rates, prenatal litter size, and fetal sex ratio (Taylor et al.

1998, Ditchkoff et al. 2012). Estimation of fetus age from fetal crown-rump measurements can indicate conception and parturition dates (Henry 1968). Pigs do not retain placental scars, and, as such, scar counts are not useful for assessing litter size in this species.

Vaginal implant transmitters (VITs) used in conjunction with GPS collars on pregnant sows have proven effective for locating farrowing nests and neonatal piglets (Keiter et al. 2017a). Information gained can include assessment of postnatal litter size and nest and neonate characteristics. Additionally, use of VITs enable researchers to mark neonates for survival studies (see above). However, when implanting sows with VITs, accurate determination of pregnancy status (e.g., with a portable ultrasound) is essential to avoid implanting sows that are not pregnant.

9.3.4 Abundance or Density Estimation

Perhaps the information about wild pig populations most frequently sought is population abundance or density (i.e., abundance per unit area). Measured over time, this information is useful for determining success of eradication programs, determining effectiveness of management strategies, and developing relationships between numbers of pigs and impacts on resources. Physiological and behavioral characteristics of wild pigs pose challenges to accurate estimation of abundance. Future research should develop population estimation methods that address pig-specific biological complexities, as described below.

Many density estimation methods that have been applied to wild pigs rely on traditional capture-mark-recapture (CMR) methods, where unmarked individuals are uniquely marked at first capture, and recapture attempts occur. A second class of methods, based on removal sampling, estimates abundance of an initial population using the size and rate of decline during successive removal events (Davis et al. 2016). To derive density from estimates of abundance for either class of methods, the abundance estimate is divided by the area sampled, although it can be difficult to identify representative areas associated with different capture techniques.

Simple CMR methods for estimating abundance assume that: 1) marks are permanent and detected correctly, 2) individuals have equal probabilities of capture, 3) capture rate is constant throughout the study, and 4) the population is closed to demographic changes during the study. Removal methods make similar assumptions, although assumptions about marks are not relevant. These assumptions do not hold true for most wildlife studies, but severity of the violations depends on the species.

For wild pig populations consisting of matrilineal and bachelor groups or solitary adult males (Mayer and Brisbin 2009), the assumption of individual independence is violated (Keiter et al. 2017b). A simple method of estimating abundance for social species is to censor dependent offspring (i.e., individuals younger than dispersal age) from the estimate, thus providing an estimate for the adult population only (Keiter et al. 2017b). However, development of methods that can use data from all individuals would allow for more accurate estimates of demographic processes such as growth rates and density.

Due to the social structure of wild pigs, age- and sex-based variation in movement patterns (Kay et al. 2017), and social behaviors such as potential territoriality (Sparklin et al. 2009), the assumption of equal capture rates across individuals is also often violated. Mixture models (i.e., modeling sub-groups of the data using multiple probabilistic distributions in order to adequately represent a ‘mixture’ of different processes), such as spatially explicit capture-recapture models (SECR) can potentially improve inference by accounting for heterogeneous capture rates and spatial structure of the sampling design and population. Mixture models account for sources of heterogeneous capture rates, helping to reduce bias in abundance estimates. Incorporating spatial information provides the added benefit of being able to convert abundance estimates to density, which allows for comparison of values across habitats and risk assessment (Davis et al. 2017a). However, although incorporation of data describing heterogeneous capture rates and spatial information can improve inference, it does not completely resolve issues originating from the mechanisms driving heterogeneous capture rates and can increase uncertainty (Keiter et al. 2017b). New techniques (or pig-specific experimental designs) that are robust to low movement rates (i.e., lower probability of detection at multiple detectors) and other pig-specific biology are needed.

A variety of non-invasive methods can be used for identifying wild pigs including natural marks (Sweitzer et al. 2000, Keiter et al. 2017b), biomarkers (Reidy et al. 2011, Beasley et al. 2015), or DNA from scat or hair samples (Ebert et al. 2010, 2012; Kierepka et al. 2016). Non-invasive marks can be advantageous in management applications because they require less time and are less likely to cause behavioral changes that affect inference. Ebert et al. (2010, 2012) developed hair- and scat-based DNA sampling protocols to estimate wild pig populations within a CMR framework, and determined that scat sampling was less biased because it sampled individuals more homogenously across age classes. Scat can be collected along transects on multiple sampling occasions, using an adaptive search method to improve detection (Keiter et al. 2016). In absence of rain, DNA degradation rate in scat samples can be low over a 5-day period (Kierepka et al. 2016); however, degradation rates vary by habitat.

If CMR methods are to be used to inform effects of management (i.e., culling) on populations, data should be collected before and after control, and data collection involves procedures not necessarily conducted by management alone. Thus, when the management objective is control or eradication, an estimation method that does not require effort beyond pig removal work is most desirable. Removal sampling can be an efficient approach for estimating abundance or density in high-density populations because it relies only on documentation of removal efforts (Davis et al. 2016). Removal models estimate initial abundance by considering the number removed and search effort. Thus, data on the number removed can be divided by initial abundance to estimate the proportion removed due to control, which eliminates the need to do pre- and post-management measurements to evaluate management effects. However, as with other abundance or density estimation methods, removal models require data from multiple sampling events from the same population, which can be rare in some management contexts. Also, removal models only perform well when abundances are moderate to high (Davis et al. 2016). Thus, other metrics of population status such as site-level occupancy (which has positive relationships to abundance; Passy 2012) may be more useful for evaluating population changes once populations are at low levels (Davis et al. 2017b).

Similar to CMR models, removal models also assume a closed population. In managed areas adjacent to unmanaged areas, where immigration into the managed area may be high, use of CMR or removal models could lead to overestimation of abundance (Hanson et al. 2008). Future work on adapting CMR and removal models for open populations using pig demographic data will facilitate planning allocation of management resources by providing: 1) less biased estimates of density, 2) estimates of immigration rates from unmanaged areas, and 3) integration of long-term control and monitoring into a single framework. One method for relaxing the assumption of demographic closure is to use an integrated monitoring and management algorithm which combines a removal model with a dynamic population model, using removal sampling data as inputs (Chee and Wintle 2010).

Density is a more informative metric of population size than abundance because it can be compared across management areas of different sizes. However, to convert abundance to density an estimate of the area sampled is required. This typically requires knowledge of local animal movements, which vary regionally and seasonally due to behavior, food availability, weather, and landscape (see Chapter 3). Some analytical methods (e.g., SECR) can explicitly account for animal space use and thus estimate density, although others, including removal models, lack an inherent measurement of space use and require additional data on animal movements or other assessments of the area sampled to convert abundance to density. In the absence of local animal movement data estimating the area sampled can be challenging, and less attention has been given to methods of estimating area sampled relative to methods of estimating abundance, presenting an important research gap.

Lastly, Lewis et al. (2017) used biotic and abiotic factors to predict wild pig density on a global scale. Factors included in the model were determined based on locations of 129 wild pig populations from 5 continents, with complimentary density estimates reported in the literature. This study used generalized linear models and model selection techniques to evaluate relative importance, magnitude, and direction of the relationship for a suite of biotic (e.g., agriculture, vegetation cover, and large carnivore richness) and abiotic (e.g., precipitation and potential evapotranspiration) factors in predicting wild pig population density. In addition to predicting densities of existing populations, this information could be used to predict the potential of this invasive large mammal to expand its distribution globally.

9.3.5 Molecular Techniques

Molecular tools are providing new insights into wild pig ecology and information critical for population control, with contributions ranging from elucidating population dynamics (see above section on density estimation), describing feeding habitats, delimiting populations or management units, and detecting pigs through environmental DNA (eDNA).

Much work has been devoted to documenting wild pig diet from stomach content analysis, which has recorded a seemingly endless list of plants, animals (both invertebrates and vertebrates), and fungi consumed by pigs (Ballari and Barrios-García 2013, Ditchkoff and Mayer 2009; see Chapters 3, 7). It has been documented that the diet of wild pigs is predominantly plants, but in their invasive range almost every wild pig stomach investigated has had animal material in it (Ballari and Barrios-García 2013, Ditchkoff and Mayer 2009). Readily digestible animal-based diet items may be hard to detect and likely underrepresented in traditional stomach content analysis (Ditchkoff and Mayer 2009, Valentini et al. 2009). Molecular-based metabarcoding diet analyses uses next-generation sequencing (NGS) to target a specific gene shared across taxonomic groups (e.g., plants, animals, fungi) by simultaneously sequencing all DNA extracted from a fecal sample (Valentini et al. 2009). Fecal samples typically are removed from the colon of a culled animal or collected fresh (within 24 hours of deposit) from transects (Robeson et al. 2018). Collection of fresh fecal material is critical for this method as DNA degrades rapidly once in the environment due to effects of UV radiation, bacteria, and weather (Santini et al. 2007). The goal of Robeson et al. (2018) was to develop a molecular approach for studying wild pig diets, rather than to quantify diet composition for a specific population. However, several intriguing results from this study suggest the utility of this approach for a more robust understanding of wild pig diet across the various ecosystems they occupy and for detecting diet changes throughout the year. With only 8 pigs sampled in Texas, but targeted at a time and place where quail were nesting, 1 pig's diet was largely composed of quail DNA (Robeson et al. 2018). In California a pig was documented to have consumed a Panamint kangaroo rat (*Dipodomys panamintinus*), which has a restricted distribution in the Mojave Desert (Robeson et al. 2018). Thus the continued application of this method promises to reveal further insights into wild pig diets and the damage they impose on flora and fauna across both their native and invasive global ranges.

While metabarcoding studies offer new insights into wild pig diets, care must be taken to understand the biases and limitations of this approach and develop appropriate sampling schemes. Some environments affect degradation more than others, and across much of the invasive range of wild pigs in the United States, degradation is rapid due to hot, humid environments (Kierepka et al. 2016). It is important to understand that any set of primers used to amplify DNA of broad taxonomic groups will introduce biases and better amplify some species' DNA fragments over others (Deagle et al. 2013, 2014; Elbrecht and Leese 2015). Further, the process of NGS relies on library preparation for targeted fragments, potentially introducing additional biases (Shokralla et al. 2012). It may also be the case that DNA that is more common in a sample may be all that gets amplified, thus missing rare items in the diet sample (Vestheim and Jarman 2008). These biases can include preferential amplification of host DNA when target DNA is for other vertebrates (Deagle et al. 2006, Robeson et al 2018). These biases may be overcome by using primers that block amplification of pig DNA (Vestheim and Jarman 2008, Robeson et al. 2018), and by collecting fresh fecal samples from ground transects as exterior epithelial cells deposited from the pigs intestinal tract have begun to degrade but the prey item's DNA is still robust on the interior of the fecal sample

(Robeson et al. 2018). These issues are known and continue to be better understood and controlled (Thomas et al. 2016). In the meantime it is critical to understand these potential biases when framing a study of wild pig diet. Even with these issues, using NGS metabarcoding to identify wild pig diet items allows for detection of animal and plant species with comparison of relative abundances of these items across geographical regions and throughout extended time periods to assess changes in diet. Further, molecular methods allow for processing of hundreds of samples in a single run, whereas stomach content analyses are extremely time intensive and sample sizes are often limited. Thus, molecular methods may allow unprecedented insight into impacts of wild pigs on native and invaded ecosystems, although costs associated with these methods are often high.

Use of DNA to study wild pigs has been more prolific in Europe than in other regions (Goedbloed et al. 2013, Podgórski et al. 2014). In Europe, wild boar are native and thus what we learn about this species in that region may not inform us about wild pigs in their invasive ranges. In North America, some studies have revealed the invasion history, dispersal patterns, and population structure of wild pigs (see Chapter 2). Mitochondrial DNA (mtDNA) sequences, which are maternally inherited, have been used to infer historical and recent movements of wild pigs in California (Sweitzer at al. 2015), across the United States (McCann et al. 2014) and Chile (Aravena et al. 2015). These studies found historical introductions from multiple sources and ongoing movement by humans. However, employing mtDNA to study wild pigs in their invasive range is likely less useful than nuclear markers that are bi-parentally inherited, due to the recent history of this invasion and ongoing long-distance movements facilitated by humans. For example, fine-scale population level studies have been conducted in Florida using 52 microsatellites (Hernandez et al. 2018), and in California using 43 microsatellites (Tabak et al. 2017). Both studies benefited from high sample sizes of pigs and molecular markers with high variability, demonstrating wild pigs have low dispersal and thus highly structured populations. Both studies also provided clear evidence that human-mediated movements of pigs is ongoing. Molecular studies that demonstrate human-mediated movements of wild pigs largely infer this because haplotypes or genotypes generally associating with a certain geographical area show up in a distant location. However, Tabak et al. (2017) used a modeling approach and conclusively demonstrated human-mediated movements and associations of movements with human economic interests that contribute to this problem.

Another method for using molecular data to explore wild pig evolution and ecology is to use high-density single nucleotide polymorphism (SNP) arrays (Ramos et al. 2009) that genotype individuals at approximately 60,000 SNP loci (e.g., PorcineSNP60 v2 BeadChip, Illumina, San Diego, California). Such high resolution molecular tools offer the capability of identifying genes that are under selection in certain populations and derive inferences about environmental influences across their range that positively or negatively affect those traits. With this level of genetic information it is unnecessary to employ other genomic reducing methods to randomly sample the genome (e.g., genotyping by sequencing, RAD Seq). However, obtaining whole genome sequences of mitochondria or ultimately sequencing whole genomes of individuals will allow understanding of differences in adaptation among individuals and populations. Although this technology is now accessible, the costs are still prohibitive for population level assessments, which require large sample sizes. Overall, with the large microsatellite panel and SNPs currently available we should be able to better understand breeding behavior, dispersal patterns, and estimate effective population sizes of wild pigs.

9.3.5.1 Environmental DNA

Understanding biological and external factors that influence population expansion and growth of wild pigs inferred from various molecular markers would help in development of management plans for controlling this species across their invasive range; it is also important to develop tools for detecting their presence. This is especially critical when wild pigs occur in low numbers in the early stages of an invasion or after implementation of population control. Detection of species in low numbers through amplification of DNA from environmental samples (eDNA; Taberlet et al. 2012) is a tool that contributes meaningfully to a suite of detection tools (e.g., cameras, tracking plots). The ability to detect pig DNA from water has been developed and deployed (Williams et al. 2017, Davis et al. 2018), allowing for detection of pigs after they have visited a water body even when there is only a single pig to detect (Williams et al. 2018). Even after just snout to water contact and with sampling occurring 15 minutes after initial contact, 3/3 samples were positive for pig eDNA (Williams et al. 2018). The utility of this approach is clear but as with all surveillance tools, there are limitations (Goldberg et al. 2016). In particular, eDNA does not distinguish between wild and domestic pigs, so it can only be effectively used in watersheds where no domestic pigs are located (Williams et al. 2018). Further field deployment and modeling have shown that sampling from smaller water bodies (wildlife guzzlers or small wallows, generally not more than 10 m diameter) produces a significantly higher probability of detection than from larger water bodies (ponds or moving streams; Davis et al. 2018). Even given these limitations, the ability to detect pigs in the environment from water samples provides a powerful surveillance tool that can be easily and inexpensively applied (Williams et al. 2016, 2018).

9.3.5.2 Pathogen Surveillance

Wild pigs carry numerous pathogens and parasites that can affect humans, livestock, and native wildlife (Bevins et al. 2014; see Chapter 5). Since wild pigs were introduced to the United States from Europe and Asia, there is concern that they may be more resistant to pathogens that do not currently exist in the United States, and thus potentially serve as a reservoir for pathogens to naïve species (Bevins et al. 2014). Given these concerns, use of rapid molecular diagnostic tools and ongoing pathogen surveillance in wild pig populations are critical to early detection of epizootics. The USDA/APHIS/Wildlife Services conducts regular and ongoing antibody surveillance of wild pig populations for a variety of pathogens including exposure to brucellosis, pseudorabies, and classical swine fever (Pedersen et al. 2014; see Chapter 5). These pathogens are tested by using various serological diagnostics. Once a pathogen is detected, then DNA sequences can be obtained through Sanger sequencing and phylogenetic or network analyses can be used to understand the origin of the pathogen. Thus molecular tools are critical to our surveillance of pathogens and our ability to understand transmission pathways.

9.4 POPULATION CONTROL

Considering the resiliency and adaptability of wild pigs, research to improve control techniques (e.g., trapping, shooting, and fencing) and development of new, innovative methods (e.g., toxicants, vaccines, contraceptives) is crucial. Equally important is development and assessment of cost-effective, integrated management approaches to reduce wild pig populations and associated damage (Campbell and Long 2009b).

9.4.1 Physical Methods

Research on current lethal control methods is generally focused on ways to improve efficiency and cost-effectiveness. For example, studies have evaluated efficacy of various trap designs (Gaskamp 2012), gate dimensions (Metcalf et al. 2014), and gate styles (Long and Campbell 2012, Smith et al. 2014). Research also has evaluated numerous baits and attractants used for wild pig trapping (Wathen et al. 1988, Campbell and Long 2008, Williams et al. 2011, Lavelle et al. 2017), but further research to identify attractants that are specific to pigs would help increase trapping efficacy and cost-effectiveness. Snares have also been used as an effective control technique, particularly in rugged terrain where conditions for trap use are unsuitable (Anderson and Stone 1993, West et al. 2009), but further research focused on improving techniques to selectively snare wild pigs is needed. Similarly, thermal imaging and night vision have substantially increased shooting efficiency and effectiveness, but research has not determined cost-effectiveness and efficacy for large-scale population reduction (West et al. 2009).

The effects of commonly employed lethal control measures (e.g., controlled shooting, aerial gunning, recreational hunting, and trapping) on remaining wild pigs could have negative implications if removal methods cause pigs to disperse, thereby increasing risk of disease transmission, potentially spreading the problem elsewhere, and hindering overall management (Fischer et al. 2016). Drive hunts with dogs in 2 separate studies conducted in Germany both had little impact on home range size of wild boar (Sodeikat and Pohlmeyer 2003, Keuling et al. 2008), and Campbell et al. (2012) found there was minimal effect on space use of wild pigs subjected to trapping, controlled shooting, drive shooting, and helicopter removals. Similarly, Campbell et al. (2010) reported that home range size and core area use was not altered due to aerial gunning from a helicopter, and it was therefore concluded to be a suitable control method in response to a disease outbreak. Conversely, research has also shown that a dispersal response can depend on the level of removal pressure. For example, areas of utilization and daily movement rates of wild pigs in southern Missouri were not affected following an initial simulated removal event, but increased after a second removal event was implemented (Fischer et al. 2016). Scillitani et al. (2010) also found that wild boar in Italy that were hunted multiple times per month increased their ranges and movement rates compared to those that were only hunted once per month. The dispersion likelihood of wild pigs following removal events is an important factor to consider when determining optimal management programs, but additional research is necessary for wildlife managers to make well-informed management decisions.

The Judas pig technique has been an important component of several successful control programs and may be particularly useful when trying to eliminate few remaining pigs in a population or in large, remote areas (McIlroy and Gifford 1997, Parkes et al. 2010). However, there is debate as to which sex or age class may serve as the best Judas pig candidate and whether or not inducing sows in estrus is advantageous (McIlroy and Gifford 1997, Wilcox et al. 2004, West et al. 2009, Parkes et al. 2010). Future research to ascertain the most suitable individuals, distance pigs will travel to find others, and length of time to locate new groups after a removal effort has occurred will help bolster the Judas pig method. Such research will also improve efficacy and cost-effectiveness of control programs by informing wildlife managers of the best locations to focus removal efforts (Beasley et al. 2018).

There is a continued need for research to improve and develop effective non-lethal control methods for wild pig management in addition to lethal methods. Recent research has evaluated the efficacy of different fence types under varying levels of motivation to either contain (e.g., disease outbreak scenario) or exclude (e.g., protection of agricultural crops) wild pigs from specified areas. Reidy et al. (2008) found that a 2-strand polywire electric fence effectively reduced sorghum (*Sorghum bicolor*) crop damage and provided a relatively inexpensive temporary fencing option for wild pigs. A 1.1-m high netted wire mesh fence with steel corner posts and a barbed wire strand buried at the base of the fence was reported to reduce damage to floodplain lagoons (Doupé et al. 2010). An innovative design involving low-level fencing (i.e., 86 cm in height) has been developed to exclude wild pigs from game feeders, but still allow access for white-tailed deer (Rattan et al. 2010). However, while certain fence designs (e.g., electric fencing) may prevent pigs from accessing areas of interest, such as agricultural fields, they may not be suitable when pigs are highly motivated to breach. Lavelle et al. (2011) tested the efficacy of 4.8-m × 0.86-m hog panel fencing to isolate wild pigs to a confined area during a simulated disease outbreak and found that hog panels were ~ 83% successful in containing pigs during simulated depopulation trials with paintball guns and 100% successful during aerial gunning trials from a helicopter. The authors concluded that even greater success probably would have been achieved if 1.3-m–1.5-m tall hog panels had been used, and that hog panel fencing could be successfully implemented for disease control and damage management. Baiting stations have also been explored as a means to contain wild pigs within a specified area during depopulation events, but were found to be an ineffective alternative to fencing (Campbell et al. 2012).

Repellents have tremendous potential for damage management given olfactory sensitivity of wild pigs, but research has yet to discover effective ways to implement these tools. Several odor and gustatory repellents currently marketed to prevent wild pig damage failed to reduce crop damage or tortoise (*Testudo hermanni hermanni*) nest predation (Vilardell et al. 2008, Schlageter and Haag-Wackernagel 2012a, 2012b). In another study, 3 commercial repellents (Morkit®, Tree Guard®, and Hot Sauce®) were found to decrease intake of seed or shelled corn by captive wild pigs, indicating that use of these products had potential to reduce depredation damage to seeded corn immediately after sowing (Santilli et al. 2003). Frightening devices also may reduce damage, but Schlageter and Haag-Wackernagel (2011) found that blinking LED lights were ineffective at deterring wild pigs from bait sites. Dakpa et al. (2009) tested a large-scale system that combined an intermittent and simultaneous shrill sound (electric horn with a frequency of 480 Hz, sound pressure of 100 dB and acoustic range of more than 274 m) with a bright light (500-watt inflorescence bulb), which proved effective in keeping wild pigs away from various types of crops over several months. However, wild pigs typically habituated to chemical repellents and frightening devices currently available, thus providing short-term solutions at best (Massei et al. 2011).

9.4.2 Pharmaceuticals

Delivery mechanisms are an essential component of pharmaceutical development for wild pig control. Baiting may be a practical and effective option for broad-scale pharmaceutical distribution, but bait consumption by wild pigs and non-target species needs to be evaluated to determine optimal baiting strategies and risk to non-target species (Campbell et al. 2006, Beasley et al. 2015). Biomarkers have been used as a cost-effective tool to measure bait uptake for a diverse range of free-ranging wildlife species, and several studies have evaluated their utility in wild pigs (Campbell et al. 2006, Massei et al. 2009, Reidy et al. 2011, Beasley et al. 2015, Baruzzi et al. 2017). Biomarkers such as tetracycline hydrochloride and iophenoxic acid can be integrated into baits and are suitable long-term markers as they can be detected for several months post-ingestion (Campbell et al. 2006, Massei et al. 2009, Reidy et al. 2011). Rhodamine B also is an effective biomarker for assessing bait uptake in wild pigs that is detectable in guard hair and whiskers for several months post-ingestion (Beasley et al. 2015, Baruzzi et al. 2017, Webster et al. 2017). In many circumstances Rhodamine B may prove to be a more favorable biomarker for assessment of large-scale pharmaceutical bait consumption and delivery due to simple collection and affordable detection from hair samples, compared to more labor intensive collection and expensive detection from blood (iophenoxic acid) or bone (tetracycline hydrochloride; Beasley et al. 2015). Preventing non-target species consumption of pharmaceuticals is also crucial both from safety and cost-effective standpoints. Results from a study in south Texas using iophenoxic acid marked baits demonstrated that a large proportion of non-target species (i.e., raccoons (*Procyon lotor*) and opossums (*Didelphis virginiana*)) consumed baits intended for wild pigs (Campbell et al. 2006), highlighting the importance of developing wild pig-specific systems for delivering pharmaceutical baits (discussed in more detail below).

Development of a wild pig-specific bait station/feeder is also crucial for safe use and future registration of any pharmaceutical in the United States (Campbell et al. 2013b), but presents a significant challenge because it needs to adequately administer the toxicant or other pharmaceutical to substantial proportions of wild pig populations while also prohibiting access to numerous non-target species (Snow et al. 2017b, Lavelle et al. 2018). Several designs have been tested including the Boar-Operated-System™ (Massei et al. 2010) and the Hog-Hopper™ (Lapidge et al. 2012), both designed to take advantage of wild pig rooting behaviors by requiring them to lift a gate with a handle using their snout for access (Snow et al. 2017b). Additionally, Snow et al. (2017b) have designed a prototype bait station that utilizes rooting abilities of wild pigs after discovering a threshold of ~13.6 kg lid resistance prohibited access by raccoons, but still permitted access by wild pigs. Research is also ongoing to develop methods to exclude black bears (*Ursus americanus*).

9.4.2.1 Contraceptives

Interest in utility of contraceptives for wild pig management has increased amidst rising pressure from the public for humane, non-lethal control techniques. However, no contraceptives are currently registered for wild pigs in the United States. Contraceptives applicable to wild pig management would ideally be species-specific, inexpensive, cause infertility to a substantial percentage of the population, be administered orally in a single dose that causes infertility for the life of the individual, and cause no or minimal adverse side-effects (Massei et al. 2012). While a contraceptive meeting all the above requirements has yet to be developed, advancements in immunocontraceptive research, particularly with gonadotropin-releasing hormone (GnRH) injections, shows considerable potential for rendering wild pigs infertile (Killian et al. 2006, Massei et al. 2012). GnRH injections produce antibodies that inhibit hormones necessary for reproduction, thereby preventing ovulation and spermatogenesis (Massei et al. 2012). Killian et al. (2006) administered 2 different doses of GnRH to female wild pigs captured in Florida and held in outdoor pens and found that pregnancy was prevented 36 weeks after administration in all pigs receiving the higher dose, and 80% of pigs that received the lower dose. Additionally, Massei et al. (2012) reported infertility for at least 3–6 years following a single GnRH dose in 11 of 12 captive female pigs. Research has also found that GnRH injections do not appear to have an effect on behavior or activity of pigs (Massei et al. 2012, Quy et al. 2014). However, an injectable form of GnRH is impractical for broad-scale management applications, requiring additional research for alternative delivery options such as oral administration. The development of oral contraceptives, phage display, and cytotoxins is currently under investigation, but further research is needed before becoming available for wild pig management (Samoylova et al. 2012, Campbell et al. 2017, D. Eckery, USDA/APHIS/WS/National Wildlife Research Center, personal communication).

9.4.2.2 Vaccines

Wild pigs serve as disease reservoirs for several dozen known pathogens that can pose significant threats to domestic livestock, wildlife, and/or humans (Barrios-García and Ballari 2012; see Chapter 5). Particular concerns exist for the domestic swine industry, where wild pigs are an obstacle to eradication of several diseases (e.g., pseudorabies, swine brucellosis, and classical swine fever (CSF)) that can cause substantial economic losses (Hahn et al. 2010, Miller et al. 2013, Rossi et al. 2015). Although culling is a primary countermeasure for controlling diseases, vaccines can be effective for reducing disease risk and prevalence. However, vaccines have not been used extensively for wild pig management in the United States to date (West et al. 2009). Elzer (1999) successfully vaccinated wild pigs against brucellosis by administering an oral vaccine in a corn syrup, corn, and pecan mixture. Researchers in Europe also tested and utilized bait formulations with live attenuated vaccines to reduce CSF prevalence for over 15 years, but these vaccine campaigns are expensive, require dissemination of vaccines multiple times per year, and there are no species-specific delivery methods (Rossi et al. 2015). Bacillus Calmette-Guerin (BCG) and heat-killed *Mycobacterium bovis* vaccines have also been developed and tested with promising results for control of tuberculosis (Beltrán-Beck et al. 2012). Piglets are an important age class for vaccination (Ballesteros et al. 2009a), but Brauer et al. (2006) found that piglets did not consume vaccine-laden baits. Thus, researchers have attempted to develop baits specifically designed for 2–3-month old piglets (Ballesteros et al. 2009b). Marker vaccines have also been examined as an alternative to commonly used live attenuated vaccines, which allow serological differentiation between infected and vaccinated animals (Feliziani et al. 2014). Similar to contraceptives, further research is required before becoming applicable for broad-scale management in the United States (West et al. 2009).

9.4.2.3 Toxicants

Research focused on development of toxicants for use in the United States as an additional management tool has great potential for efficient and cost-effective population control of wild pigs. Sodium fluoroacetate (1080) and yellow phosphorus have been used to control wild pigs in Australia, but have not been approved for use in the United States, primarily due to questions regarding humaneness and risks to non-target species (Cowled et al. 2008, Snow et al. 2017a). Kaput®, a warfarin-based toxicant (Poche et al. 2018), was recently registered as the first toxicant for wild pigs in the United States by the Environmental Protection Agency (EPA), but as of this writing has not been approved for operational use. One of the major challenges in developing a wild pig toxicant is creating a toxicant that is highly toxic to pigs, resulting in rapid and humane death, while also minimizing secondary hazards and risks to non-target species (Cowled et al. 2008). In an effort to address this challenge, researchers have been developing HOGGONE® (Animal Control Technologies Australia P/L, Victoria, Australia), a sodium nitrite-based toxicant for wild pigs to eventually be registered through the EPA for use in the United States (Snow et al. 2017a). Sodium nitrite induces a humane and rapid death to wild pigs upon consumption due to methemoglobinemia, reportedly within 3–4 hours, where pigs experience a loss of consciousness then death from hypoxia (Cowled et al. 2008, Snow et al. 2017a). Sodium nitrite has also been purported to pose minimal secondary hazard risks (Lapidge et al. 2012, Snow et al. 2018). A sodium nitrite-based toxicant known as BAIT-RITE Paste® has already been approved for use in New Zealand and pen trials with BAIT-RITE in New Zealand and HOGGONE in the United States achieved approximately 90% and 95% mortality, respectively (Shapiro et al. 2016, 2017a).

9.4.3 Integrated Management

Optimizing integrated management approaches that are specifically designed for individual control programs is imperative for planning cost-effective wild pig control (Campbell and Long 2009b). An informative and strategic decision-making process is useful for determining how specific integrated management approaches can be implemented within desired time frames. Recent advancements in research towards improving integrated wild pig management has been explored through modeling and take into consideration savings associated with resources protected as well as cost of control (Davis et al. 2017b). For example, bioeconomic models have been used to assess helicopter gunning and 1080 toxicant use as cost-effective control options to reduce lamb predation by wild pigs (Choquenot and Hone 2000). Models suggested annual helicopter removals were more profitable than using 1080 toxicant in terms of control costs vs. reductions in lamp predation if pasture biomass was above a certain threshold. However, once pasture biomass decreased below that threshold, toxicant use became more profitable because of increased bait uptake by wild pigs. These models demonstrate the importance of having a firm understanding of control techniques and various factors that impact efficacy, such as utilizing toxicants during periods of low natural food abundance. Similarly, Krull et al. (2016) demonstrated the most effective interval for harvesting wild pigs to consistently reduce ground disturbance damage was every 3 months. However, costs associated with a 3-month harvest interval were also considerably higher, such that the investment may not be worth the return in damage reduction. Continued modeling research similar to the above examples, which link pig population dynamics to damage and assess efficacy and cost-effectiveness of control programs are imperative for future success of wild pig control. Given the complexity of issues associated with management of invasive wild pigs, a substantial challenge to maximizing efficacy of integrative management is development of models scalable across regions that vary by environmental attributes and account for differing management objectives and stakeholder interests. In addition, there is a need to better link management efforts to both population demographics and reductions in damage, both at the local and regional scales.

9.5 DAMAGE ASSESSMENTS

It is well known wild pigs have far-reaching impacts, both directly and indirectly, on a range of ecosystems, habitats, native species, and agricultural crops (Bevins et al. 2014; see Chapter 7). Thus, to better understand the magnitude of damage and inform management decisions aimed at reducing the numerous damage types caused by wild pigs, it has become increasingly imperative to quantify these impacts with accurate techniques (Engeman 2000, Bengsen et al. 2014). Further, damage monitoring strategies should be a fundamental basis of any control program to assess efficacy of wild pig population control on natural or agricultural resources (Bengsen et al. 2014). Research on development of damage indices is no longer solely focused on the number of wild pigs removed because pig numbers do not necessarily equate to damage amounts (Melzer et al. 2009). Hone (2012) modeled effects of varying wild pig harvest rates on damage reduction and found the pig population needed to be reduced dramatically to observe changes in damage because the relationship between density and damage was saturating (damage amount increased exponentially with low pig densities and was saturated at high pig densities). Researchers are working to improve current damage assessment methods and utilize technological advancements to develop new methods that can be efficiently conducted in practical and cost-effective manners, while still producing accurate estimates of damage.

9.5.1 Agricultural Damage

Assessing agricultural crop damage by wild pigs is an important step in mitigating economic losses crop producers experience, but accurately quantifying crop damage is often difficult for numerous reasons including spatial and temporal variation of damage (Bengsen et al. 2014, Bleier et al. 2017). As a result, few practical step-by-step procedures have been developed to accurately assess damage on a broad scale (Bengsen et al. 2014, Michez et al. 2016), which has compelled researchers to develop new methods that can be easily implemented to quantify damage to a variety of crop types. For example, Engeman (2017) developed a practical damage assessment method applicable to a variety of row crops. This technique is applied shortly after planting, a particularly susceptible time for crop damage by wild pigs (Schley et al. 2008, Bleier et al. 2017), by quantifying field size, distance between rows, and cumulative length of damage along all rows of the field. A similar method has been developed for assessing damage to low-growing row crops just prior to harvest (Engeman and Ondovchik 2017). Although recent improvements to ground-based agricultural damage assessments have been explored, additional research leading to methods that can be applied more universally is needed.

Technological advancements in remote sensing, particularly with unmanned aerial systems (UAS), has promising applicability for efficient, cost-effective, and accurate agricultural damage assessments (Anderson and Gaston 2013, Michez et al. 2016, but see Gentle et al. 2011). UAS can readily provide imagery with extremely high spatial and temporal resolution capable of distinguishing crop damage caused by wild pigs (Michez et al. 2016). Considering the potential of UAS for agricultural damage assessments, Michez et al. (2016) compared a ground-based method to 2 UAS-based methods to estimate damage to corn prior to harvest. A fixed-wing UAS was flown over fields to obtain imagery, which was converted into orthophotos through photogrammetric processing. Damage was then estimated by either visually delineating areas of damage into polygons in ArcGIS or with crop height models to differentiate between damaged and undamaged plants. Both UAS methods reduced total assessment time by 75% or greater, but tended to underestimate total damage compared to the ground-based method. The authors concluded that UAS assessments were a viable method to estimate crop damage, but also recommended ground-based methods for cross-validation. Additionally, research is currently underway to develop effective UAS-based tools and techniques to assess wild pig damage for a variety of crops including corn, soybeans, and peanuts. Multiple UAS platforms and sensors are being tested, as are autonomous flight software packages that systematically fly and collect data over damaged crop fields (Figure 9.6). Further developmental research is required to evaluate and optimize UAS-based crop damage assessments, but should prove to be extremely valuable for future damage assessments.

9.5.2 Damage to Ecosystems and Native Species

The extensive range of wild pigs and their destructive foraging behavior results in numerous impacts to ecosystems and native species that can be difficult to quantify (Thomas et al. 2013, Murphy et al. 2014, Keiter and Beasley 2017). Protocols to assess damage are often context specific depending

FIGURE 9.6 Aerial photos taken by UAS (a) showing extensive damage to corn fields by wild pigs, and (b) ability of UAS to detect wildlife damage to crops not visible to ground personnel walking or driving field edges. (Photos (a) by M. Lutman and (b) by S. Smith. With permission.)

on the type of impact and local environment (Fagiani et al. 2014). Damage quantification is further complicated by trying to find a balance between adequate sample size to accurately detect impacts and practical utilization of available resources, resulting in an overall lack of suitable methods to quantify the broad range of damage wild pigs cause (Thomas et al. 2013, Fagiani et al. 2014). In response to a scarcity of suitable damage assessment techniques, Fagiani et al. (2014) developed a statistically robust monitoring procedure to assess rooting effects in a lowland forest in central Italy on richness, diversity, and abundance of understory plants, invertebrates, and small mammals by comparing areas with low and high rooting damage. The authors concluded that their sampling framework could be used as an initial guide for developing assessment procedures and then tailored for specific objectives and area sampled. Additional assessments to quantify damage have recently been tested including Engeman et al. (2016), who quantified fine-scale rooting disturbance over a 5-year period to ecologically sensitive plant communities with numerous threatened and endangered species in south-central Florida. This technique though, may be impractical in many damage assessment situations considering the amount of time and resources required to complete. Thomas et al. (2013) optimized a more practical line-intercept method that was applicable to a variety of damage types through testing in Florida wetland sites. Damage was measured along evenly spaced transects, summed as a single total across all transects, and then divided by total length of all transects rather than averaging the proportion of damage for each transect line separately. The development and optimization of additional damage assessments designed to be practically implemented yet produce accurate estimates for numerous types of impacts are needed.

9.6 CONCLUSIONS AND FUTURE DIRECTIONS

Over the last several decades research has grown on the ecology and management of wild pigs throughout both their native and invasive ranges (Figure 9.1). These efforts have greatly improved our understanding of the basic biology and ecology of wild pigs, but have also led to substantial advancements in tools and technologies to capture, handle, study, and manage this important invasive species. While many of these advancements have benefited from more broadly developed technologies (e.g., molecular tools, telemetry, UAS technology, and more widespread access to cellular and satellite networks, night vision, and thermal technologies), others are a direct result of research on wild pigs and integration of a wider breadth of research expertise now focused on this species. Despite these advancements, compared to other ungulates in North America wild pigs remain a surprisingly understudied species. Thus, there remains a critical need for additional research on the ecology, management, impacts, and human dimensions associated with wild pigs (Beasley et al. 2018). Researchers also would be wise to take advantage of the growing amount of data being generated across the range of wild pigs by synthesizing these datasets (e.g., Kay et al. 2017) to develop more comprehensive and broadly applicable conclusions to aid the management of this destructive invasive species.

In most cases, management of wild pigs requires eventual euthanasia of captured individuals to reduce population size and associated damages. As a result, research on intact populations can be perceived as in direct conflict with short-term achievement of management goals. However, the ultimate goal of most wild pig research is to inform and improve management success, but research endeavors are costly and may take several years to complete, thus diminishing relevance to immediate management objectives. Nonetheless, advancements from research are essential to continued improvement of management techniques and strategies. In situations where ongoing management is occurring or necessary, we suggest researchers take advantage of such opportunities whenever possible to maximize resources and direct the application of research goals to management needs in an adaptive management framework. In particular, further development of methods and modeling approaches that allow for estimation of density and other demographic or vital parameters from culled individuals, and use of samples collected from these animals would minimize potential conflicts between research and management objectives (e.g., Davis et al. 2016). Indeed, such an approach has been applied widely among numerous wild pig studies to date and can be useful for developing an adaptive management strategy for wild pig removal programs.

Tools and techniques necessary to capture and study wild pigs have been around for centuries, yet research continues to yield novel insights into the ecology, impacts, control, and human dimensions of this species, all of which are essential to improve management success. While many future advancements will stem from further application of new or improved tools (e.g., molecular methods, tracking technologies), there also remains a need for refinement of basic tools necessary to capture and handle wild pigs. For example, advancements in trap designs to capture trap-shy pigs and development of baits and attractants that are selective for wild pigs and can be used during big game hunting seasons in areas that prohibit baiting are needed (Beasley et al. 2018). Furthermore, as new information or technology becomes available research must be amenable to the shifting needs of managers tasked with reducing wild pig populations. For example, current interests in application of toxicants or other pharmaceuticals to control wild pigs necessitates research to address the efficacy and impacts of such control options. However, until research and funding on wild pig ecology and management are prioritized by a greater number of state and federal wildlife agencies, the ability of researchers to address outstanding and future research needs will be limited.

ACKNOWLEDGMENTS

Contributions from M.J.L., K.M.P., A.J.P., and K.C.V. were supported by the USDA. Contributions from J.C.B. were partially funded by the US Department of Energy under award # DE-EM0004391 to the University of Georgia Research Foundation. Contributions from J.C.K. were funded by the US Department of Energy through the USDA under Interagency Agreement DE-AI09-00R22188. Mention of commercial products or companies does not represent an endorsement by the US Government.

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