Critical Review of Potential Control Tools for Reducing Damage by the Invasive Rose-ringed Parakeet (*Psittacula krameri*) on the Hawaiian Islands

Page E. Klug[1†], William P. Bukoski[2], Aaron B. Shiels[3], Bryan M. Kluever[4], and Shane R. Siers[5]

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[1] USDA APHIS Wildlife Services National Wildlife Research Center, North Dakota Field Station, Fargo, ND

[2] USDA APHIS Wildlife Services, Hawaii State Office, Kauai, HI

[3] USDA APHIS Wildlife Services National Wildlife Research Center, Rodents Project, Fort Collins, CO

[4] USDA APHIS Wildlife Services National Wildlife Research Center, Florida Field Station, Gainesville, FL

[5] USDA APHIS Wildlife Services National Wildlife Research Center, Hawaii Field Station, Hilo, HI

[†] Study director, corresponding author: page.e.klug@usda.gov

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Executive Summary

Aims and Goals

Rose-ringed parakeet (*Psittacula krameri,* Scopoli; hereafter RRPA) are present on the Hawaiian Islands of Kaua'i, O'ahu, and Hawai'i. The RRPA is an invasive bird that can cause economic damage and is a threat to natural resources and human health and safety. A single pair of RRPA were introduced on Kaua'i in the 1960s. The current population estimate is 6,800 birds as of 2018 with documented exponential growth. RRPA are major pests of agricultural crops world-wide and in Kaua'i and O'ahu have been shown to negatively impact seed crops including corn (*Zea mays*) and soybeans (*Glycine max*) as well as fruit crops including lychee (*Litchi chinensis*), longan (*Dimocarpus longan*), rambutan (*Nephelium lappaceum*), and many others. Invasive parakeets pose a risk to natural resources through the dispersal of invasive plant seeds, destruction of native seeds, and competition with and aggression toward native wildlife. Invasive parakeets are a potential threat to human health and safety through unsanitary conditions and the risk of disease transmission to livestock and humans in agricultural fields or urban roosts. The alarming increase in invasive RRPA on the island of Kaua'i, and the damages they cause, has compelled multiple stakeholder groups to appeal for immediate action. However, uninformed reactionary measures may not be cost-effective and may worsen the problem (e.g. shooting at roosts may simply disperse roosting birds to inaccessible areas). Thus, our objective was to complete a comprehensive, critical review of bird damage management tools and their potential use for controlling parakeet damage on the Hawaiian Islands. Specifically, we reviewed, summarized, and interpreted existing information to evaluate the potential effectiveness of damage management tools for RRPA and the best strategies for deployment. We used the behavior and ecology of RRPA to inform our tool recommendations and their potential efficacy under various damage scenarios (e.g., urban, agricultural). We identified candidate tools for further evaluation in lab and field studies and provided guidelines for actions that can be taken to protect stakeholder assets at this time.

Recommendations and Conclusions

We recommend an integrated pest management strategy including lethal and non-lethal tools specific to the damage problem and surrounding environment. The effects of non-lethal tools are temporary given RRPA learn quickly and habituate to threats without a negative stimulus. Thus, success with non-lethal tools requires combining multiple techniques and changing or moving them regularly. Lethal removal of birds in local damage situations is not effective for population control. To alleviate damage through population reduction, a well-funded, coordinated, and sustained lethal campaign is required at broad scales. Future research should include an adaptive management plan for population suppression in addition to lab and field-based tests of non-lethal tools and their effectiveness at reducing RRPA damage on the Hawaiian landscape.

The primary management tools for population reduction of RRPA include shooting with limited use of trapping at foraging sites and hand net capture at roosting sites (Table 1). We recommend shotguns for moving birds and air rifles for precise removal of birds perched in crops or roosting trees. Shooting strategies should be applied in a manner that does not simply disperse birds, compromising the ability of managers to access nesting and roosting sites. Further research is needed on fertility control via contraceptives given functionality on Kauaʻi may be limited by inability to establish feeding stations due to abundant alternative food resources and potential nontarget consumers. Currently, no toxicants are approved by regulatory agencies for RRPA.

The primary management tools for reducing RRPA damage at agricultural sites include 1) modifying the crop and surrounding habitat, 2) exclusionary devices, and 3) frightening devices (Table 2). Habitat suitability for RRPA can be reduced by altering the timing, siting, spacing, and crop varieties used in agricultural practice. We recommend a) growing sensitive crops away from RRPA flight routes, loafing sites, and night roosts, b) eliminating early and late-maturing crops in the same locality to avoid birds establishing a feeding site, c) advancing harvest date to limit the damage period, d) delaying disking or destruction of unused crops to provide alternate forage, and e) using large plots and reducing space between plots due to damage being greater at field edges. Habitat suitability can be reduced by altering the surrounding landscape by a) removing loafing areas near the crop to be protected and b) providing alternative forage by planting lure crops in extra tillable space and not harassing birds in the lure crop. Exclusionary devices can deter RRPA from entire crop fields and orchards (e.g., netting over entire trees and plots) or simply limit access to the part of the plant to be protected (e.g., bags, netting, or plastic over fruiting bodies only). We recommend multiple visual and auditory frightening devices used in combination and reinforced with a negative stimulus (i.e., lethal shooting). Promising tools include lasers due to parakeets visually perceiving laser lines as startling, drones due to the ability to access hard-reach areas for hazing, and bioacoustics due to noises that occur naturally in the environment (e.g., RRPA distress calls or predator sounds) may reduce habituation.

The primary management tools for reducing RRPA damage at roosting sites include 1) habitat modification and 2) frightening devices (Table 3). Habitat suitability for RRPA can be reduced by limiting perch space including the use of alternative landscaping not preferred by RRPA (e.g., short native loulu palm) or trimming preferred roost trees. We recommend visual frightening devices used in combination and reinforced with a negative stimulus (shooting). In areas with high human density, auditory devices are not practical due to noise pollution. Promising hazing tools include lasers and water devices to cause reflexive withdraw or make the roost undesirable.

Legal and Regulatory Status

Legal Aspects

RPPA are nonnative and not protected by the United States Migratory Bird Treaty Act. RRPA are not listed as an injurious species under the US Lacey Act (18 U.S.C. 42), but are listed by the State of Hawaiʻi (http://dlnr.hawaii.gov/dofaw/files/2013/09/Chap124a.pdf). This designation prohibits the release, transport, or export of RRPA with importation restricted by the Hawaiʻi State Department of Agriculture. All wild birds including introduced species are protected under Hawaiʻi Revised Statues (HRS183D and HAR124), thus a nuisance wildlife control permit must be obtained through the Hawaiʻi Department of Land and Natural Resources to lethally take RRPA. Various avian repellents are registered by the US EPA and State of Hawaiʻi with label specifications for various habitats. Follow all state and local regulations for firearm discharge (HRS-134; https://web.archive.org/web/20111129064310 / http://www.honolulupd.org/info/gunlaw.htm) and laser use under Hawaiʻi Revised Statues (HRS-136; lasers https://www.laserpointersafety.com/rules-general/uslaws/uslaws.html).

Disclaimer

Wildlife can threaten the health and safety of you and others in the area. Use of damage prevention and control methods may pose risks to humans, pets, livestock, non-target animals, and the environment. Be aware of risks and take steps to reduce or eliminate those risks. Some methods this document may not be legal, permitted, or appropriate in your area. Check with personnel from your state wildlife agency and local officials to determine if methods are acceptable and allowed. Mention of any products or brand names does not constitute endorsement, nor does omission constitute criticism.

Table 1: Lethal removal options at foraging and roosting sites impacted by rose-ringed parakeets (suggested methods in gray).

LETHAL METHOD	DESCRIPTION	NOTES
Shooting	Lethal removal by firearm	Shotguns for incoming birds and air rifles for precise removal while perched in crop or tree at foraging sites; air rifles for precise removal while perched in roost tree (depredation permit required)
Traps & Hand Nets	Capture with baited live-traps or spring-loaded traps on ground or platform; hand-held nets	Traps not practical in roosting areas or foraging areas with preferred crops or where bait is not enticing; long-handled hand nets not practical for foraging birds but effective at capturing birds at accessible roosting locations (e.g., low fronds); (depredation permit required)
Toxicants	Lethally control pest birds with toxic bait	No toxicants available for RRPA
Fertility Control	Control populations by limiting fertility & reproduction	Diazacon shown effective on RRPA in captivity; functionality on Kauaʻi limited by inability to establish feeding stations due to abundant alternative food
Predators	Use falconry or provide predator habitat to attract natural predators	Falconry is expensive and labor-intensive; promoting predators not practical in Hawaiʻi with limited native predators and not wanting to promote invasive predators

Rose-ringed Parakeets

Physical Description

The rose-ringed parakeet, also known as the ring-necked parakeet, is distinguished by bright green plumage and red bill (Figure 1). The RRPA is a medium to large parakeet at 110-182 g and a 40 cm wing span and the tail (up to 25 cm) approximately the same length as the body (38-42 cm) with some blue-green and yellow coloration (Butler 2003). The sexes are dimorphic with mature males (>3 years old) having a dark pink or reddish to black neck-ring, a black lower mandible, and longer tails than females. Juvenile males do not have the diagnostic neck-ring and cannot be distinguished from females based on plumage aside from primary feather tips being rounder in adults (Butler and Gosler 2004). Additionally, juveniles may have greyish-white irises where adult irises are yellowish (Forshaw and Cooper 1989), but this did not hold for introduced populations in Britain (Butler and Gosler 2004). Female and immature male RRPA were successfully discriminated using biometrics of wing length, bill length, and number of yellow-underwing greater coverts (Butler and Gosler 2004). The RRPA is a popular species in aviculture due to the ability to produce color mutations (e.g., yellow, light green, blue, blue-green, grey, and albino) (Low 1992), thus color may vary in introduced populations with releases from the pet trade. Fertile hybrids have been documented with the Alexandrine parakeet (*Psittacula eupatria*) further increasing potential variation in biometrics (Krause 2004). Annual feather molt typically occurs post-breeding from May to July in the introduced population in Britain, but molt occurs from May to December in the native range of India (Butler and Gosler 2004). Primary molts take more than one year with the potential for

Table 2: Damage reduction options for agricultural foraging sites impacted by rose-ringed parakeets (suggested methods in gray).

TOOL OR METHOD	DESCRIPTION	NOTES
Modify Crop & Habitat	Reduce habitat suitability; alter agricultural timing, siting, spacing, and crop varieties; manage habitat surrounding crop fields; provide alternative forage (e.g., lure crops)	Grow crops away from flight lines, loafing sites, and night roosts; eliminate early and late-maturing crops in same locality; use large plots; reduce space between plots (damage greater at field edges); advance harvest date; remove RRPA loafing areas near crops; delay disking or destruction of unused crop; plant lure crop in extra tillable space and do not harass birds in lure crop
Netting & Wires	Enclose crops/trees using temporary or permanent netting or overhead wires	Netting offers complete exclusion; can be expensive and labor intensive; RRPA move through overhead wires thus requires narrow openings & teepee design over trees
Bagging Crops	Place bags over fruiting body during damage window period	Offers exclusion when alternative food available; inexpensive; moderately labor intensive; reduce duration of bagging to limit insects and mold
Lasers	Broadcast lasers (automated or hand-held) over the top of the crop	Acts as frightening device; labor intensive (hand-held) or expensive (automated units); lasers are potential eye hazard
Visual Deterrents	Deploy effigies (dead RRPA, predator models, hawk eyes) or novel objects (reflective, wind-propelled objects or mobile drones)	Varied results depending on flock, landscape, and deployment strategy; more effective if used in combination with auditory deterrents and reinforced with negative stimulus (shooting); drones can reach inaccessible areas
Auditory Deterrents	Deploy loud noises (pyrotechnics, cannons); bioacoustics (RRPA-specific distress/alarm calls, predator noises), or sound to mask avian communication (sonic nets)	Habituation occurs faster with loud blasts than bioacoustics that mimic natural threats; reduce habituation by switching, combining, and moving devices; sonic nets effective if alternative food and natural predators present
Methyl anthranilate	Spray chemical repellent to act as irritant	Foliar application at harvest is available; effective field application strategies depend on crop; temporary effects

Table 3: Damage reduction options for urban or suburban roosting sites impacted by rose-ringed parakeets (suggested methods in gray).

TOOL OR METHOD	DESCRIPTION	NOTES
Modify Habitat	Reduce habitat suitability/reduce perch space; replace landscaping; net roost trees	Trim roost trees (e.g., royal palms) realizing excessive trimming weakens trees; use alternative landscaping and native plants (e.g., loulu palm); netting not practical for every tree and not visually pleasing to humans
Lasers	Broadcast lasers (automated or hand-held) at the roost tree or incoming birds	Acts as frightening device; labor intensive (hand-held) or expensive (automated units); lasers are potential eye hazard
Water Spray	Use water spray to cause birds to reflexively withdraw from roost	May reduce appeal of roosting space; does not harm vegetation; labor intensive unless system installed
Visual Deterrents	Deploy effigies (dead RRPA, predator models, scarecrows, hawk eyes) or novel objects (reflective, wind-propelled objects, or drones)	Varied results depending on flock, landscape, and deployment strategy; more effective if reinforced with negative stimulus; auditory deterrents not practical in urban areas (noise pollution); drone use not allowed over crowds, thus limited applicability in urban areas
Methyl anthranilate	Spray chemical repellent to act as irritant	Fogging applications available but include restrictions near water; not practical around human activity (odor pollution)

suspended molts early in the molt season as a way to identify juvenile male RRPA (Butler and Gosler 2004). Identifying the age structure, sex ratios, and survival rates of the population would assist in modeling populations and identifying effort needed for population reduction over time (Butler and Gosler 2004).

Vocalizations and Hearing

As RRPA congregate in evening roosts, they make noisy, loud, screechy descending “kee-ak” … “kee-ak” … “kee-ak” sounds (www.audubon.org). Communication between RRPA include a general aggregation call (soft “krr”), a predator alert or conspecific confrontation call (deep “krr”), and the call of the young (“yak, yak, yak”), among others (e.g., food source signaling) (Bashir 1979; Kotagama and Dunnet 2007). Detection of RRPA is facilitated by their loud, gregarious communication improving the ability to monitor populations (Hart and Downs 2014). The auditory sensitivity of most birds is between 2-5 kHz with diminished sensitivity beyond this range (Beason 2004; Dooling 1982). The details of RRPA hearing have not been evaluated but other psittacine species (i.e., the budgerigar and cockatiel) have low frequency sensitivity, whereas passerines are more sensitive at frequencies above 6 kHz (Okanoya and Dooling 1987). Understanding the hearing ability and communication calls of RRPA will inform the effective use of sound-based deterrent strategies.

Distribution and Range

RRPA are native to southern Asia (Indian subcontinent) with two subspecies (*P. krameri borealis* and *P. krameri manillensis*) and central sub-Saharan Africa with two additional subspecies (*P. krameri krameri*

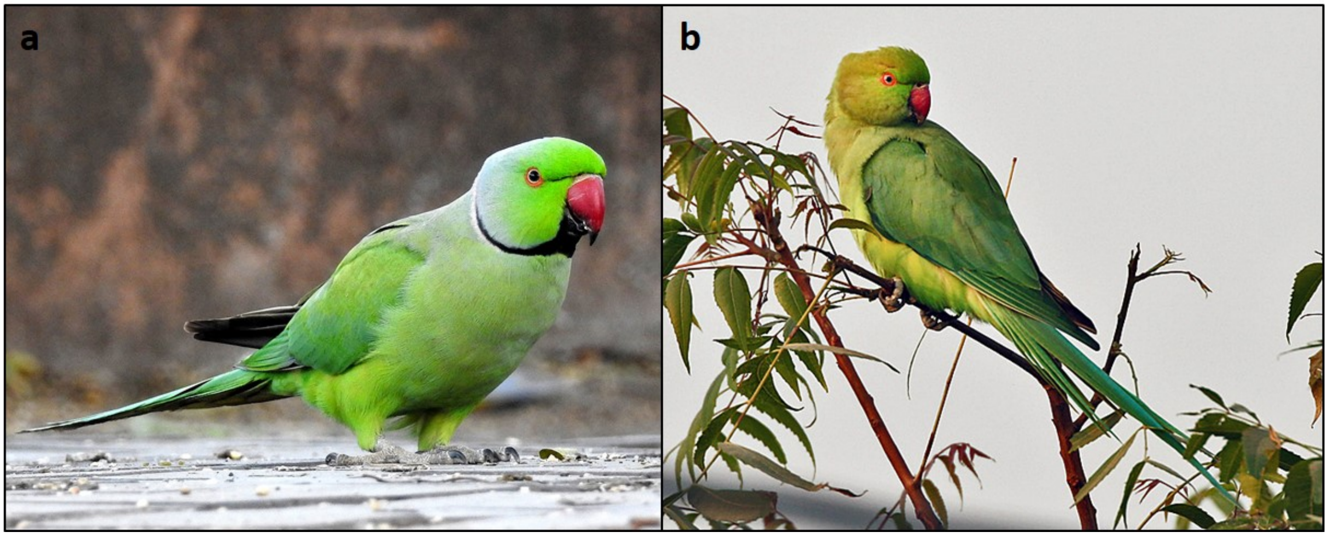

Figure 1: a) Male and b) female rose ringed parakeets (*Psittacula krameri*) (Photo by Raju Kasambe).

and *P. krameri parvirostris*; Morgan 1983; Figure 2a). RRPA are one of the most successful bird invaders in the world with sightings in over 76 countries and introduced populations in more than 35 countries (Invasive Species Compendium 2012; Menchetti et al. 2016; Figure 2b). Introductions range from tropical to temperate locales and reports in the United States include Alabama, California, Florida, Hawaiʻi, Louisiana, Texas, and Virginia (Uehling et al. 2019). Introduced populations are established in Africa (Algeria, Egypt, Kenya, Libya, Seychelles, South Africa), Australia, Asia (Hong Kong, Japan, Philippines, Singapore, Thailand), the Middle East (Afghanistan, Bahrain, Iran, Iraq, Israel, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, United Arab Emirates, Yemen), Central and South America (Cuba, Puerto Rico, Venezuela), and Europe (Belgium, Crete, France, Germany, Greece, Italy, Netherlands, Portugal, Slovenia, Spain, Turkey, and United Kingdom) (CABI 2018). Most temperate invasive populations are from India (Jackson et al. 2015), due to the constraint of reproductive timing (Luna et al. 2017). The success of this global invader is due to its generalist diet, tolerance of humans, and prevalence in the pet trade (Clergeau and Vergnes 2011; Mori et al. 2013b; Strubbe et al. 2015).

Introduced RRPA populations are expanding and linked to anthropogenic habitats where temperature limitations can be ameliorated (Czajka et al. 2011; Tayleur 2010). Balmer et al. (2013) indicate that RRPA have increased their breeding range by 4,400% since 1968, making it one of the most rapidly increasing species. The probability of occurrence for RRPA is best predicted by human density (Hugo and Van Rensburg 2009). RRPA are commensal species with humans where trees occur, but thrive with cultivated areas for foraging, where they do considerable crop damage (Dean 2000; Smallwood 1994). Historical introductions of RRPA in New York City did not establish, suggesting distributional limits due to climate (Bull 1973; Roscoe et al. 1976). Though expansion into temperate regions should not be dismissed, given RRPA are capable of inhabiting areas colder than their native range due to human modification of the environment (Strubbe et al. 2015). Introductions in warm climates ensure high fertility, and thus risk of population establishment, growth, and spread is greater (Shwartz et al. 2009).

RRPA have been reported on Hawaiʻi, Kauaʻi, Maui, and Oʻahu (Runde et al. 2007). The species was introduced to Kauaʻi, when a few birds were released by a Lawai bed-and-breakfast in the 1960s. By the 1980s the population was at 50 birds followed by an exponential increase with estimates at 2,000 birds in 2011 and 6,800 in 2018 (Figure 3). This exponential population growth continues to be evident even with an estimated 100-200 birds lethally removed in a given year (Avery and Shiels 2018). RRPA on Kauaʻi have not likely reached carrying capacity, based on the carrying capacity estimated in the greater London area to be around 32,000 (Fletcher and Askew 2007;

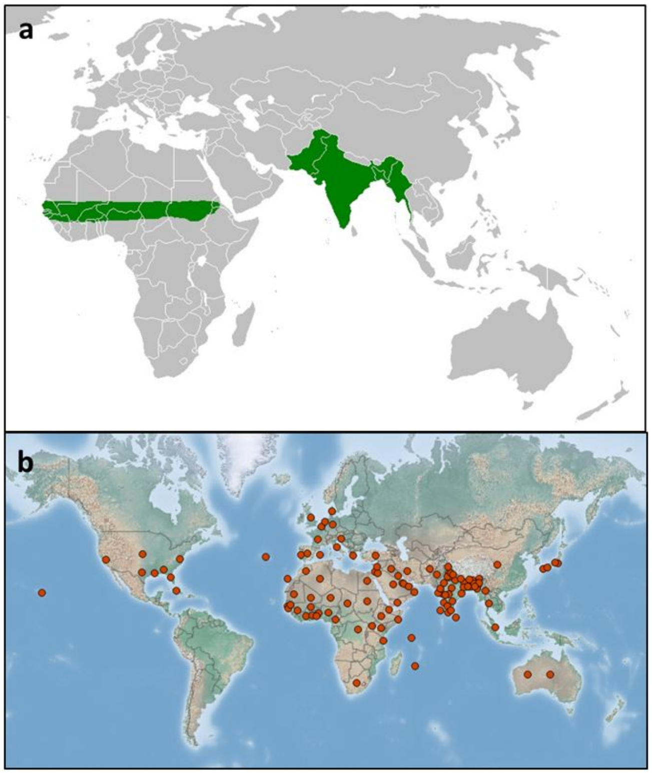

Figure 2: Maps of the a) native range and b) introduced range of the rose-ringed parakeet (*Psittacula krameri*) (CABI 2018).

Peck 2013), a region that has more limited food resources compared the Hawaiian Islands. The estimated RRPA population sizes on Oʻahu are 3,200 and an estimated 6-8 adults established on Hawaiʻi (Big Island, Puna) (Avery and Shiels 2018).

Population Growth and Spread

Many introduced bird species show an initial slow population growth, known as a lag phase, followed by exponential growth (Dean 2000; Runde et al. 2007). RRPA show a 34 year lag from first introduction to a rapid increase in population growth, highlighting that areas with low numbers of RRPA may in time become problematic (Aagaard and Lockwood 2014). Although low reproductive output at low densities is evident in introduced species (Lewis and Kareiva 1993), RRPA in Kauaʻi have likely moved past the lag phase on the species invasion curve (Figure 3). Annual growth rates at roost sites in the Rhine-Neckar region of southern Germany showed a 14% annual increase (Braun 2009).

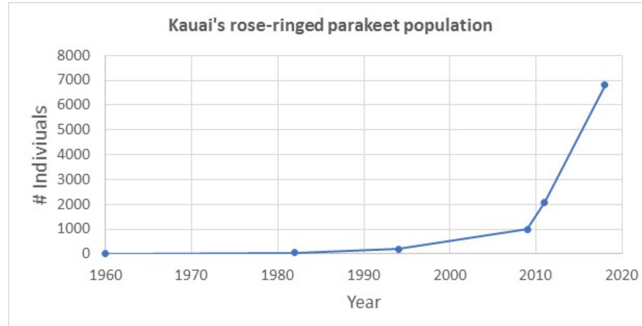

Figure 3: Nonnative rose-ringed parakeets (*Psittacula krameri*) population estimates on Kauaʻi (1960-2018). Estimates are minimum number known alive based on visual surveys. The 1960-2009 data was collated by Bill Lucy (KISC) using Bishop Museum records, and the 2011 and 2018 counts occurred at the two known roosts (i.e., Koloa/Lawai and Lihue).

In the United Kingdom, Butler et al. (2013) witnessed an intrinsic rate of increase of ~0.27 between 1996 (1,500 birds) and 2004 (10,000), which was ~27 years after the first breeding pair was found in 1969. This finding places high importance on eradicating a population while still in the lag phase, as might be found on other Hawaiian islands (e.g., Hawaiʻi) or even mainland United States (e.g., Florida and California), where urban populations do not appear harmful but may become damaging after completion of a lag phase and dispersal to agricultural landscapes (Strubbe et al. 2015). Future changes such as climate change, urbanization, habitat alterations, or species adaptations may cause what was once thought to be a harmless, nonnative species to become a harmful invasive (Bauer and Woog 2011). For RRPA this has already occurred on Kauaʻi, and is capable of happening on mainland United States given the species' pest status in their native range, especially with increasing suburban spread into historically agricultural areas (Bendjoudi et al. 2013; Strubbe et al. 2015). Owre (1973) indicates that invasive parakeets in Florida may be "time bombs" given their reputation as agricultural pests combined with the scale of production in winter produce in the state. Thus, effective population reduction or eradication campaigns are not only important for the Hawaiian Islands but other areas of the United States.

RRPA in England have shown range expansion at only 0.4 km/yr, but with population growth at approximately 30% annually (Butler 2005) and other European invasions showing an average of 19% growth (Pârâu et al. 2016), dispersal may increase. The population of RRPA in the Netherlands increased the number of breeding pairs by 1,582% and an increase in distribution of 239% since 1998 (van Kleunen et al. 2010). Monk parakeets (*Myiopsitta monachus*) have shown long-distance dispersal capabilities as invaders (100 km) that contrasts with dispersal distances in their native range (2 km) (Da Silva et al. 2010). That said, monk parakeets in their native range have shown range expansion of 2.1 to 7.6 km/yr as the preferred habitat increased and was connected by urban environments acting as stepping stones (Bucher and Aramburú 2014).The potential distributions of RRPA in Italy and Belgium were mapped using bioclimatic models and ecological niche modelling, both indicating large areas of suitable but unoccupied habitat (Di Febbraro and Mori 2015; Strubbe and Matthysen 2009c). Lambert et al. (2009) indicate RRPA are capable of breeding in northern regions of the United Kingdom (UK) and thus northern expansion is possible, especially with rapid population growth where RRPA are established. The dispersal of RRPA across Kaua'i will likely increase as the population grows exponentially.

Reproduction

RRPAs reach maturity at approximately 1.5 years and acquire their mature plumage at 2.0 to 2.5 years (Butler 2003). Population suppression should focus on breeding pairs to have mortality outpace recruitment, otherwise breeding pairs will be able to effectively replace any nonbreeding individuals removed from culling operations (Grarock et al. 2014; Newton 1998). In the UK, male sub-adults, identified by the lack of a pink neck-ring, were found reproducing, indicating that breeding can occur before males acquire their adult plumage (Butler et al. 2013), placing further importance on culling females as the potential best route to decrease population growth.

Nesting season in the native range is from January to April but can extend from December to August (Alī and Ripley 1969; Kotagama and Dunnet 2007). The breeding season in the UK is from February to July (Butler et al. 2013). Sperm production occurs between January and March in India with regressed testes during the rest of the year (Krishnaprasadan et al. 1988). Courtship and pair formation in captive RRPA was observed in early December to January, and nest selection was completed from January to February (Gokhale et al. 2000). Courtship displays include mate preening and the female spreading her wings and moving her head from side to side, while the male struts on the branch and raises one foot (Paton et al. 1982). Groups of 2-5 parakeets have been seen searching for nest cavities (Sarwar et al. 1989). Both male and female RRPA showed increased "peeping" into nest cavities from May to June and August to October with a decline in July (Kotagama and Dunnet 2007). Females occupy and defend nest cavities long before the first egg is laid. Female RRPA showed a higher incidence of being at the nest from December to April with substantial increases in July (Kotagama and Dunnet 2007). Thus, population suppression measures should be focused prior to or during breeding to limit annual recruitment. Those tasked with lethal removal should be aware of sex-specific breeding behavior to be able to target females at the nest cavity if having to make a choice on which bird to remove.

RRPA are cavity nesters and breeding pairs can be single or loosely grouped, sometimes in the same tree (Czajka et al. 2011; Khan et al. 2004). The preferred nesting trees have large diameters with abundant shrub understory, but orientation of cavity does not matter (Butler et al. 2013). In the UK, nests were found >8 m high in trees with a diameter at breast height (DBH) of 74 cm and a height of 20 m (Butler et al. 2013). Larger trees were used in India with a 120 cm DBH (Simwat and Sidhu 1973), as well as in Pakistan where trees with a diameter >50 cm contained more nest cavities (Ali et al. 1981). As trees mature, availability of nesting cavities increases for larger-bodied birds (Battisti and Dodaro 2016). In urban settings, cavities within human structures are used extensively, and RRPA will use nest boxes when natural cavities are limited (Braun 2007; Grandi et al. 2018; Symes 2014). In Belgium, RRPA nests were found in old woodpecker nests, natural cavities, and nest boxes; parakeet abundance was positively related to cavity abundance (Strubbe and Matthysen 2007). In Pakistan, Eucalyptus spp. are used by nesting RRPA (Khan 1999) and are an abundant introduced tree species on the Hawaiian Islands. In Kauaʻi nesting habitat includes the invasive albizia tree (*Falcataria mollucana*) where hollows created from fallen branches of mature trees provide nesting cavities (Gaudioso et al. 2012).

RRPAs are weak excavators and can create cavities but mainly modify existing holes for nesting with entrances $\geq$4 cm and averaging 8-10 cm (Butler 2003; Czajka et al. 2011; Khan and Beg 1998; Waseem et al. 2015). RRPAs bite off bark around cavities, which may be sign of an active nest (Kotagama and Dunnet 2007). On Kauaʻi, the outside of the cavities are often stained orange either from the iron-rich soil or resins in the wood (W. Bukowski, pers. comm.). RRPA cannot enter holes <40 mm (Strubbe and Matthysen 2009b). The internal cavity of a nest found in an ʻoʻhia lehua tree (*Metrosideros polymorpha*) was measured at 15 x 12 x 35 cm (Paton et al. 1982). RRPA use the same cavity repeatedly in subsequent breeding seasons (Orchan et al. 2013). Identifying active cavities could provide locations for which to return for lethal removal, otherwise the hole could be filled to restrict future breeding.

Females begin incubating after the first egg with an egg laid every 1-2 days, which causes asynchronous hatching. Eggs are spotless, white, and glossy with a mean weight of 8.42 g (Gokhale et al. 2000). Female nestlings outperform males in growth measurements; later hatching chicks are also smaller than early-hatching chicks (Braun and Wink 2013). Females leave the nest during incubation to feed in the morning and evening but rarely leave the nest during the first 8-10 days of brooding (Gokhale et al. 2000). The incubation stage lasts 22-24 days. Male RRPA feed females during incubation and brooding with an average of four visits/hour and may perch near the cavity for nest guarding (Hossain et al. 1993; Shivanarayan et al. 1981). Females feed nestlings by regurgitation (Hossain et al. 1993; Mabb 1997a). The nestling stage is 49 days with fledglings leaving the nest at 6-7 weeks (Lamba 1966). Fledglings rely on parental assistance for two weeks (especially the male) to learn food selection, after which juveniles separate from adults and flock together (Braun and Wink 2013). Removing adults during the breeding season will reduce nesting success and fledgling survival, thus recruitment.

The median clutch size for RRPA is four eggs, yet two are generally fertile, and two fledglings per nest are common (Butler et al. 2013; Hossain et al. 1993; Lamba 1966; Lambert et al. 2009; Pithon and Dytham 1999; Shivanarayan et al. 1981; Simwat and Sidhu 1973). RRPA will renest if eggs are removed from the nest (Lambert et al. 2009). RRPA rear one brood a year (Butler et al. 2013), although second clutches have been documented in the native range (Hossain et al. 1993). The potential for unrestricted breeding is greater in warm tropical climates. The breeding biology of RRPA on the Indian sub-continent includes clutch size ranging from 2-6 eggs (Lamba 1966; Shivanarayan et al. 1981). Lamba (1966) examined 33 nests and found that an average of 3.0 young fledged per nest. Shivanarayan et al. (1981) examined 66 nests and found that an average of 1.7 young fledged per nest. This lower rate of reproduction was attributed to predation by crows and snakes (Shivanarayan et al. 1981). Nest predation is low in introduced populations due to limited predation pressure (Braun and Wink 2013). Where predation is uncommon, variation in clutch size is related to the size of the nest cavity (Butler et al. 2013). In Europe, fledging rates averaged 1.9 young/nest (Butler 2003) and a nest survival rate of 72% (Butler et al. 2013) of 108 nests monitored during 2001-2003. Of the 12 RRPA nests inspected in the Greater London area from 1997-1998, an average of 0.8 young fledged per nest (Pithon and Dytham 1999). Causes of nest failure include incomplete development, infertility, predation, starvation, and weather (Hossain et al. 1993). Out of seven nests on Oʻahu from 2012-2013, there was an average fledgling success rate of 3.0 chicks/nest with each pair producing 2-4 fledglings, and no second clutches (Shiels and Kalodimos unpub. data). Average clutch size on the Hawaiian Islands is not reported, but a nest cavity on Oʻahu contained four eggs (Shiels and Kalodimos unpub. data). The nesting success of RRPA is likely high given endangered Hawaiian forest birds have high reproductive success compared to mainland tropical species (Hammond et al. 2016). RRPA are cavity nesters and aggressively attack potential predators, thus the likelihood of nest survival is high. Conditions on Kauaʻi are favorable for high reproductive success due to 1) abundant food year round, 2) nest cavities not being limited with proliferation of albizia trees, and 3) limited predation. Establishing a birth rate for RRPA on Kauaʻi will inform the necessary number of RRPA culled in a given year to reduce the population size.

Survival and Mortality

Mortality has to exceed recruitment from breeding for effective population control. RRPAs have low mortality in captivity and the wild. In captivity RRPA generally live for 20 years (Pithon 1998) and may live as long as 34 years (Brouwer et al. 2000). The estimated survival rate of RRPA in the wild is unknown, but the endangered Puerto Rican Parrot (*Amazona vittata*) has an annual survivorship of 0.675 in the first year followed by increased survivorship of 0.848 (Snyder et al. 1987).

Increased predation can limit population growth of RRPA (Bendjoudi et al. 2013), but in many areas predation pressure is not enough to reduce growth. Potential predators on the Hawaiian Islands include small Indian mongoose (*Herpestes javanicus*), rats (*Rattus* spp.), feral cats (*Felis catus*), barn owls (*Tyto alba*), pueo (*Asio flammeus sandwichensis*), Hawaiian hawks (*Buteo solitarius*), other transient raptors, and humans (e.g., pet collectors and depredation permitees) (Hammond et al. 2016). These same predators occur on Kauaʻi in different numbers excluding the mongoose, which has not established on the island. Although the estimated survival rate of RRPA on the Hawaiian Islands is unknown, predator release likely inflates survival. RRPA have exhibited aggressive behaviors toward potential predators further limiting the ability of predators to control populations (Hernández-Brito et al. 2018).

Temperature may limit establishment, but RRPA have been successful in invading temperate regions (Butler 2005; Roscoe et al. 1976). Climatic hazards like frost and fog can induce high mortality in RRPA (Bendjoudi et al. 2013; Temara and Arnhem 1996). Increased mortality has also been shown in winter months in Belgium (Temara and Arnhem 1996), and RRPA in New York suffered frostbite (Roscoe et al. 1976), indicating cold-sensitivity may limit range expansion. Although Strubbe and Matthysen (2009a) found the introduction success of RRPA declined in areas with >50 days of frost, Thabethe et al. (2013) found RRPA are capable of temporarily withstanding cold temperatures of 5°C. RRPA are capable of surviving snow storms in Italy, given food is still available (Fraticelli 2014). Food resources or the energy budget of RRPA are not likely to be negatively impacted by temperatures on the Hawaiian Islands, and thus cannot be considered a significant limiting factor for RRPA populations. Tropical storms may act to reduce population numbers on the Hawaiian Islands, but RRPA are capable of surviving the monsoon season in their native range of India (Krishnaprasadan et al. 1988).

Habitat

In their native range, RRPA are found in woodlands, urban parks, and cultivated areas surrounded by trees from 0-2,000 m above sea level (Menchetti et al. 2016; Runde et al. 2007). RRPA appear to favor areas with increased human presence and structures over alternative natural areas (Lambert et al. 2009; Menchetti and Mori 2014). Urban areas in Belgium with increased tree cover, thus more nesting cavities, were shown to harbor greater numbers of RRPA (Strubbe and Matthysen 2007). Populations of cavity-nesting RRPA rely on the availability of mature, cavity-providing trees (Davis et al. 2014). In Kauaʻi, RRPA are mostly found in urban and agricultural areas but are capable of inhabiting higher elevations where native Hawaiian birds reside (Runde et al. 2007). RRPA in Kauaʻi use disturbed forests for nesting, separate from agricultural foraging and urban roosting sites.

RRPA home ranges on Kauaʻi are variable (0.11 to 6,437 ha) and 13-24 times greater than average home ranges in Brussels (75-86 ha), where urban parks are the preferred habitat for roosting, foraging, and nesting (Gaudioso et al. 2012; Strubbe and Matthysen 2011). RRPA in the UK travel 6 km a day with similarly large foraging ranges in the native range of India (Butler 2003; Chakravarthy 1998). RRPA are capable of flying long distances (e.g., 24 km in Germany; 15 km in the Netherlands) from their nocturnal roost to foraging sites (Braun 2009; Kahl-Dunkel and Werner 2002). Kaua'i is 40 x 53 km (1,430 km2), thus any point on the island could be accessed from a number of potential urban roosts.

Flocking and Roosting

RRPA are highly social and forage, roost, and nest in flocks (Peck et al. 2014; Zeeshan et al. 2016). Aggregations in nighttime roosts peak from October to January and decline thereafter with lowest levels from May to July, which may be related to the breeding season extending from January to August when females do not communal roost (Kotagama and Dunnet 2007). In some regions communal roosting areas include night roosts, day roosts, nesting cavities, and foraging trees, while in other areas roosting sites are separate from nesting and foraging (Ali et al. 1981; Khan 2002). In Kaua'i, evening roosts are located in urban and exurban areas with tall trees, especially royal palms (*Roystonea regia*), (Gaudioso et al. 2012; Sheehey and Manfield 2012). The large roosts are likely due to safety and nearby food availability on the landscape (Khan 1999, 2003; Zufiaurre et al. 2017). RRPA frequent nighttime roosting areas 30-60 minutes before sunset (Mabb 1997b). RRPA are active from dawn to dusk leaving up to 30 minutes before sunrise and returning up to 20 minutes after sunset (Khan 2002; Luna et al. 2017). Observations of RRPA indicate increased activity in the morning and evening with inactivity or resting midday (Kotagama and Dunnet 2007). The introduced population in Venezuela exhibits a 1:1 ratio of juveniles to adults (Nebot 1999). Small foraging flocks of males have been documented, with adults regurgitating food for juveniles after aggressive harassment (Nebot 1999). If this situation is observed, adult males should be removed first, which will also decrease juvenile survival.

Food Habits and Feeding Behavior

Nutritional needs of psittacine species are well known due to captive rearing (Koutsos et al. 2001). RRPA diet mainly includes dry and fleshy fruits and seeds but also nectar, vegetables, and flower buds (Alī and Ripley 1969; Clergeau and Vergnes 2011). RRPA are known to be a major pest of agricultural crops world-wide (Alī and Ripley 1969; Butler 2003; De Grazio 1978; Manchester and Bullock 2000). RRPA have been documented damaging cereals and oil crops such as corn (*Zea mays*), sunflower (*Helianthus annuus*), safflower (*Carthamus tinctorius*), sorghum (*Sorghum* spp.), bajra or millet (*Pennisetum* spp.), rice (*Oryza sativa*), sesame (*Sesamum indicum*), wheat (*Triticum* spp.), barley (*Hordeum vulgare*), soybeans (*Glycine* spp.), mustard and cole crops (*Brassica* spp.), lentils (*Lens* spp.), and oil palm (*Elaeis* spp.). RRPA are also pests of fruits and nuts such as almonds (*Prunus dulcis*), ber (*Ziziphus mauritiana*), mangos (*Mangifera* spp.), dates (*Phoenix* spp.), grapes (*Vitis* spp.), pomegranates (*Punica* granatum), mulberries (*Morus* spp.), guava (*Psidium* spp.), peaches (*Prunus persica*), apples (*Malus* spp.), citrus (*Citrus* spp.), lychees (*Litchi chinensis*), longan (*Dimocarpus longan*), rambutan (*Nephelium lappaceum*), papayas (*Carica papaya*), passion fruit (liliko'i; *Passiflora edulis*), sugarcane (*Saccharum officinarum*), and coffee (*Coffea* spp.) (Babu and Muthukrishnan 1987; Bashir 1979; Chakarvorty et al. 1998; Dhindsa and Saini 1994; Eason et al. 2009; Forshaw and Cooper 1989; Garrett 1998; Gupta et al. 1997; Hart and Downs 2014; Koopman and Pitt 2007; Mukherjee et al. 2000; Patel et al. 2002; Paton et al. 1982; Ramzan and Toor 1972, 1973; Reddy 1998; Saini et al. 1994; Sandhu and Dhindsa 1982; Shafi et al. 1986; Shiels et al. 2018; Shivanarayan et al. 1981; Toor and Ramzan 1974; van Kleunen et al. 2010). The closely-related monk parakeet has also been shown to damage tomatoes (*Solanum* spp.) and ornamental trees and shrubs (Senar and Domenech 2001). In evaluating RRPA stomach contents, it was found that the RRPA diets were 45% cereals, 38% tree fruits, and 16% oilseeds (Saini et al. 1994). Shiels et al. (2018) found RRPA diets on Kaua'i were 31% corn, 30% yellow guava, 28% sunflower, and 11% other items, but varied with roost location.

Feeding activity peaks in the morning (06:00-10:00) and evening (15:00-19:00) (Ali et al. 1981; Nebot 1999). The size of foraging flocks can range from a few to hundreds of birds, with larger flocks forming with a lack of harassment (Bashir 1978; Khan et al. 2006; Shafi et al. 1986). The distribution of RRPA damage is greater along edges and on taller, early maturing sunflower heads with damage lasting from 3-6 weeks (Besser 1982; Khan and Ahmad 1983b; Mukherjee et al. 2000). The damage varies with some fields hit harder due to location or timing of maturity (Khan and Ahmad 1983b). Understanding RRPA feeding behavior will help to pinpoint the spatial and temporal windows for deploying control tools.

RRPA are a serious agricultural pest with a generalist diet and various feeding behaviors that increase the severity of crop damage. RRPA attack corn at various stages by feeding on the anthers and pollen of the male inflorescence, tender cob stage (i.e., silk and green husk), and milky stage of the cob up until maturity (Ali et al. 1981; Khan et al. 2006). RRPA perch on sunflower heads and reach over to access the seeds that are hulled prior to consumption (Bashir 1978; Khan and Ahmad 1983b). Damage to fruit trees is higher on the top branches (11-60%) compared to the side and bottom (0-6%) (Shafi et al. 1986). RRPA attacking stored grains and eating unripe fruit extends the damage window (Andreotti et al. 2001; Fletcher and Askew 2007; Neo 2012; Ramzan and Toor 1972). RRPA are wasteful eaters due to the behavior of dropping food and discarding partially eaten food (Ali et al. 1981; Toor and Ramzan 1974). RRPA damage also results from spoilage of the partially eaten cobs (Khan et al. 2011).

Effects of Rose-Ringed Parakeets

Economic Effects

Invasive avian species were ranked for negative economic impact with the Canada goose (*Branta canadensis*) and RRPA earning the highest scores (Kumschick and Nentwig 2010). Invasive species pose a threat to agriculture ranging from small-scale subsistence farming to large-scale production (Mack et al. 2000; Paini et al. 2016). RRPA have been identified as agricultural pests on the Hawaiian Islands and effort is needed to stop their growth and spread (Koopman and Pitt 2007; Paton et al. 1982). Hawaiian agriculture includes fruits, vegetables, seed corn, coffee, macadamia nuts (*Macadamia integrifolia*), flowers and orchids (Orchidaceae), pineapples (*Ananas comosus*), soybeans, herbs, rice, ti (*Cordyline terminalis*), taro (*Colocasia esculenta*), potatoes (*Solanum tuberosum*), ginger (*Zingiber officinale*), honey, aquaculture, landscaping and wood products, and livestock (Koopman and Pitt 2007). In Kauaʻi parakeets have thus far been shown to negatively impact seed crops including corn, sunflower, and soybeans as well as fruit crops including mangos, lychee, longan, rambutan, guava, papaya, and passion fruit (lilikoʻi) (Koopman and Pitt 2007; Paton et al. 1982). RRPA are known to completely consume a fruit or only slightly damage it, rendering it unfit for marketing (Ramzan and Toor 1972). In India RRPA damage to sunflower can reach 97% (Reddy and Gurumurthy 2003), and Khan et al. (1983) estimated RRPA caused US$ 1.95 million of damage to ripening oilseed sunflower in Pakistan, a number that is likely greater in today's economy. In 1984, economic analyses estimated RRPA damage to citrus crops in Pakistan was US$ 2.1 million (Shafi et al. 1986). In 1975 the estimated potential loss from an established population of RRPA in California could cost US$ 735,000 based on an estimate of RRPA damaging 0.1% of the foods they are known to eat (Paton et al. 1982). In 1982 Paton et al. (1982) repeated the calculation for Hawaiʻi and estimated crop losses at US$ 50,000, not including grains. In the UK, damage to vineyards was estimated to reduce wine production from 5,000 to 3,000 bottles/year (CABI 2018). The economic impact of roosting RRPA on personal property damage and the tourism industry is unknown and the negative effects of invasive RRPA are likely perceived and experienced differently by different subsets of society. RRPA cause defoliation of ornamental trees when used as roosting habitat (van Kleunen et al. 2010), which has been reported for roosting trees in Kauaʻi (e.g., royal palms; Figure 4). Current economic impact studies on the negative effects of RRPA on agriculture, property, and tourism are needed for a full evaluation of the benefits of management interventions.

Ecological Effects

Invasive species pose a threat to native ecosystems (Mack et al. 2000), with nonnative birds having unique impacts (Martin-Albarracin et al. 2015). Biological homogenization, or loss of biodiversity, increases as urban land cover increases, resulting in the same urban-adapted, invasive species and

Figure 4: Damage by rose-ringed parakeets (*Psittacula krameri*) to a) corn (*Zea mays*) tassels (Photo by Anant Kumar), b) guava (https://www.youtube.com/watch?v=QTdLSvOSNGU), c) corn ear (Photo by William Bukowski, USDA-APHIS Wildlife Services), d) sunflower (*Helianthus annuus*; Photo by Lonely Traveler, http://icbird.blogspot.com), e) papaya (*Carica papaya*; Photo by David Havel), f) mango (*Mangifera* spp.; Photo by Karen Goh), g) ornamental flower (Photo by Georgina Chin), h) royal palm (*Roystonea regia*) roost tree (Photo by Marianne Martin).

a subsequent decline in native species across the globe (McKinney and Lockwood 1999). As seed eaters, RRPA may consume and destroy native plants such as the loulu palm (*Pritchardia hillebrandii*) and koa (*Acacia koa*) trees (Runde et al. 2007; Shiels et al. 2018). RRPA may consume flowers such as those from the native ʻoʻhia tree (Paton et al. 1982), which poses potential competition with native honeycreepers for nectar resources (Loope et al. 2001). In Australia, RRPA damage and kill trees by stripping bark, which could lead to changes in the tree community (Fletcher and Askew 2007). RRPA consume and disperse invasive plant seeds such as yellow guava (*Psidium guajava*) and passion fruit (*Passiflora edulis*) (Gaudioso et al. 2012; Shiels et al. 2018; Thabethe et al. 2015). Corn and invasive yellow guava (*Psidium guajava*) are the main food items for RRPA on Kauaʻi, which helps to sustain RRPA populations and may increase the spread of invasive plants (Shiels et al. 2018).

In addition to altering vegetation, competition with native wildlife may include resource competition for food and habitat (e.g., nesting sites) as well as disrupted foraging where native fauna may decrease feeding or increase vigilance in the presence of a dominant invasive (Charter et al. 2016; Dodaro and Battisti 2014; Mori et al. 2017; Peck et al. 2014). RRPA have shown antagonistic behaviors preventing native species access to backyard bird feeders (Le Louarn et al. 2016) and competitively outcompeted native nuthatches (*Sitta europaea*) in Belgium (Newson et al. 2011; Strubbe and Matthysen 2009b; Strubbe et al. 2010), European hoopoe (*Upupa epops*) in Israel (Yosef et al. 2016), and evicted black-collared barbets (*Lybius torquatus*) and golden-tailed woodpeckers (*Campethera abingoni*) from nests in South Africa (Hart and Downs 2014). RRPA are known to compete with spotted owlets (*Athene brama*) in their native range of India (Pande et al. 2007). In the Seychelles RRPA are considered a threat to the endemic Seychelles black parrot (*Coracopsis barklyi*) (Reuleaux et al. 2014). In Israel it was shown that RRPA can positively impact the breeding of other invasive birds (i.e., common myna [*Acridotheres tristis*]) by increasing the number of suitable nesting cavities (Orchan et al. 2013). Mammals are also impacted given RRPA are capable of displacing bats from cavities, modifying cavities so they are unsuitable, and lethally attacking bats to the point of affecting populations (Gebhardt 1996;

Hernández-Brito et al. 2018; Hernández-Brito et al. 2014a; Menchetti et al. 2014). Introduced RRPA directly attack native European fauna including little owls (*Athene noctua*) (Mori et al. 2017), Eurasian red squirrels (*Sciurus vulgaris*) (Japiot 2005; Mori et al. 2013a), and Leisler's bat (*Nyctalus leisleri*) (Menchetti et al. 2014). RRPA are also known to directly harass the Isabelline serotine bat (*Eptesicus isabellinus*) as well as kestrels (*Falco tinnunculus*) and passerine species such as Eurasian tree sparrows (*Passer mantanus*), and mob larger birds such as seagulls and herons (Dubois 2007). In Spain RRPA have been documented lethally attacking house sparrows (*Passer domesticus*), blue tits (*Cyanistes caeruleus*) (Covas et al. 2017), greater noctule bats (*Nyctalus lasiopterus*) (Hernández-Brito et al. 2018), and black rats (*Rattus rattus*) (Hernández-Brito et al. 2014b). As a cavity nester, RRPA hold the potential to impact native Hawaiian wildlife that use tree cavities or crevices including the endangered ʻōpeʻapeʻa or Hawaiian hoary bat (*Lasiurus cinereus semotus*), the puaiohi or small Kauaʻi thrush (*Myadestes palmeri*), and Hawaiʻi ʻākepa (*Loxops coccineus coccineus*) though aggression, resource competition, or spread of disease, especially if the RRPA range expands to overlap with endemic Hawaiian species.

Human Health and Safety and Wildlife Disease

Large flocks of RRPA can be of risk to humans at urban roosting sites, agricultural foraging sites, and airfields. Flocking RRPA near airports can be a threat to human health and safety through airplane strikes (Fletcher and Askew 2007; Montemaggiori 1998), with many foraging and loafing sites near the Līhuʻe Airport on Kauaʻi. The presence of large nighttime roosts in urban areas produces noise complaints (Menchetti et al. 2016; Strubbe and Matthysen 2009a; van Kleunen et al. 2010) and unsanitary conditions under roosts has been speculated to increase the risk of disease transmission to humans (Gaudioso et al. 2012; Sheehey and Manfield 2012). Additional risks of foodborne illnesses may also increase when large flocks of birds come into contact with food used for human consumption.

Invasive birds are known reservoirs and vectors of a variety of human, wildlife, and livestock diseases (Altizer et al. 2003; Fèvre et al. 2006; Lever 2005; Pimentel et al. 2000; Weber 1979). In a review of the pathogens and parasites recorded in RRPA, viruses, bacteria, protozoans, fungi, helminthes, and arthropods were found to infect domestic and wild RRPA across their native and introduced ranges (Pisanu et al. 2018). The viruses include Adenovirus-like viruses, Circovirus, Avihepadnavirus, respiratory herpesvirus, Avian Influenza A/H9N2, Papillomavirus, Paramyxovirus, Polyomavirus, and Reovirus (Bert et al. 2005; Conzo et al. 2000; Desmidt et al. 1991; Grund et al. 2002; Hulbert et al. 2015; Julian et al. 2012; Kondiah et al. 2006; Kundu et al. 2012; Mase et al. 2001; Piasecki and Wieliczko 2010; Rahaus and Wolff 2003; Sa et al. 2014; Sanada and Sanada 2001; Tsai et al. 1993; van den Brand et al. 2007; Wellehan Jr et al. 2009). The bacteria include *Chlamydia* spp., *Streptococcus* spp., and *Enteroccocus* spp. (Chahota et al. 1997; Madan et al. 2011; Piasecki et al. 2012; Pisanu et al. 2018; Sambyal and Baxi 1980; Suwa et al. 1990). The protozoans include *Cryptosporidium* spp., *Eimeria* sp., *Haematoproteus* sp., *Plasmodium* (N.) *dissanaikei*, and *Sarcocystis* sp. (Bennett et al. 1993; Cray et al. 2005; De Jong 1971; Ishtiaq et al. 2007; Morgan et al. 2000; Ryan et al. 2003; Tsai et al. 1992). The fungi include *Cryptococcus neoformans* and *Saccharomycetales* (Elhariri et al. 2015; Gokulshankar et al. 2004; González-Hein et al. 2010; Mancianti et al. 2002; Raso et al. 2004) (Mancianti et al. 2002). The helminthes include *Ascarops psittaculai*, *Ascaridia* sp., and *Raillietina* spp. (Huber et al. 1983; Schmidt 1972; Tsai et al. 1992; Webster and Speckmann 1977) The arthropods include *Argas reflexus*, *Columbicola theresae*, *Echinophilopterus tota*, *Laemobothrion* cf. *maximum*, *Psittacornimus* (N.) *lybartota*, *Paragoniocotes* sp., *Tarsopsylla octodecimdentata*, and *Turturicola salimalii* (Atiqur-Rahman-Ansari 1947; Mey 2003; Mori et al. 2015; Najer et al. 2012).

Parakeets are negatively affected by pulmonary diseases and viruses, such as beak and feather disease virus (psittacine circovirus), proventricular dilatation disease (avian bornaviruses), avian pox virus (avipoxviruses), Newcastle's disease (paramyxoviruses), and avian influenza (influenza A viruses); bacterium, such as erysipelas (*Erysipelothrix rhusiopathiae*), pasteurellosis (*Pasturella* spp.) (England 1998; Mase et al. 2001; Sa et al. 2014; Tozer 1974). Pet birds including parrots are thought to be reservoirs of the highly contagious Newcastle's disease virus that can infect domestic poultry operations (Butler 2003; Courtenay Jr and Robins 1975). RRPA are capable of acting as the vector for the bacterium *Chlamydophila psittaci*, the etiological agent of avian psittacosis, also known as ornithosis, chlamydiosis, and parrot fever (Fletcher and Askew 2007; Menchetti and Mori 2014; Raso et al. 2014). Chlamydiaceae agents (typed as Chlamydia avium) were found in a wild RRPA in France, suggesting sanitary risk from invasive parrots (Pisanu et al. 2018). To date, the 18 RRPA collected from Kaua'i and tested for avian influenza and avian psittacosis were found to be negative (Gaudioso et al. 2012).

Large flocks of birds hold the potential to harbor various diseases potentially transmissible to humans, wildlife, and livestock (Runde et al. 2007; Weber 1979). Other diseases where birds act as the reservoir or vectors include food-borne illnesses such as shiga toxin-producing *Escherichia coli* (STEC), listeriosis (*Listeria monocytogenes*), and avian salmonellosis (*Salmonella* spp.) (Carlson et al. 2011; Conover and Vail 2014; Sanches et al. 2017). Johne's disease (*Mycobacterium avium pseudotuberculosis*) is a chronic infection that can be carried by birds and infects the small intestines of ruminants (Corn et al. 2005; Shitaye et al. 2009). Arboviruses such as encephalitis and West Nile viruses (*Flavivrus* spp.) are transmitted by mosquitos and amplified by birds (Conover and Vail 2014; Nemeth et al. 2010), although parakeets have been shown to be incompetent hosts (Komar 2003). Histoplasmosis (*Histoplasma capsulatum*) is a respiratory fungal infection found in soil contaminated by bat and bird feces (Conover and Vail 2014; Quist et al. 2011).

Current and Potential Management Practices

Deterrence is desired by stakeholders for the protection of valued resources. Unless the deterrent strategies are incredibly effective and widespread enough to deprive RRPA of vital resources, such as food or nesting cavities, they would likely shift RRPA damages to resources valued by other stakeholders. Alternatively, population reduction would benefit all stakeholders, given fewer birds result in less overall damage. Thus, management techniques focused on reducing recruitment (i.e., birds entering the population) and survivorship (i.e., birds removed from population) would be the most effective for reducing RRPA damages over the long term. Population management may reduce RRPA damages by slowing or reversing their population growth and spread throughout Kaua'i. Due to the shared burden of RRPA damages, expenditures of tax funds by government agencies should prioritize population reduction techniques. The following sections summarize existing lethal and nonlethal tools for population reduction and deterrence and evaluate their potential for reducing RRPA damages.

Population Reduction and Population Monitoring

RRPA are listed by Strubbe et al. (2011) as an invasive bird that should be targeted for eradication. Substantial effort and planning has to be undertaken for an effective lethal campaign including the subset of population on which to focus and the temporal and spatial distribution of effort. A population viability analysis was used to examine the effectiveness of various management options including eradication for monk parakeets in Florida (Pruett-Jones et al. 2007). They concluded effort was needed to reduce population growth, yet it was not practical due to the number of birds and associated costs. For this particular situation, it was decided that effort should be focused on removing problematic nests and not overall population control (Pruett-Jones et al. 2007). A lethal campaign to control monk parakeets in their native range occurred in Uruguay from 1981-1982, in which eight people monitored and lethally removed 250,000 parakeets over a 509,600 km^2 area costing US$ 147,684 (Linz et al. 2015). The only known successful eradication of RRPA occurred on the Seychelles with the removal of 548 birds over five years and multiple attempts (Bunbury et al. 2019). The campaign cost approximately US$ 1 million (Tomiska 2016), lending evidence to the expense of complete eradication (Menchetti et al. 2016). Shooting combined with extensive knowledge of the birds' movement patterns, feeding areas, roosting spots, and flight lines was the most efficient method for population reduction (Bunbury et al. 2019). The last RRPA were located by campaigns that included monetary incentives for public reporting (Karapetyan 2017; Figure 5). Although incentives for reporting may be helpful to capture the last few birds, we do not recommend a bounty program on the Hawaiian Islands due to the possible proliferation of breeding programs or intentional release of RRPA to capitalize on financial incentives (Pasko et al. 2014). Monitoring RRPA is essential for evaluating the effectiveness of deterrent devices and lethal control measures. Monitoring is a vital tool in identifying population expansion, new roosts, important breeding grounds, and loafing areas and flight lines (Hart and Downs 2014). Citizen science data can be used to monitor presence and changes in abundance or distribution of RRPA as they are easily located and identified (Aagaard and Lockwood 2014; Symes 2014; Vall-llosera et al. 2017), although some may not want to disclose locations for fear of causing the birds harm (Hart and Downs 2014).

Figure 5: The Seychelles Islands Foundation (SIF) relies on public reporting to assist in the eradication of the invasive rose-necked parakeet and has used posters and monetary incentives in the elimination campaign (Karapetyan 2017) (Photo License: CC-BY).

Chemical Control

Avicides– The use of toxicants to control agricultural pests has been studied for other pest birds but has not been proposed for RRPA (Linz and Bergman 1996). Starlicide®, also known as DRC-1339, is a slow-acting avicide that is registered with the US Environmental Protection Agency (US EPA) for control of several species of pest birds, including blackbirds, starlings, pigeons, crows, ravens, magpies, and gulls (United States Department of Agriculture 2001). Distribution and use is limited to USDA-APHIS Wildlife Services employees, and requires pre-baiting and monitoring for non-targets (Dolbeer and Linz 2016). In Kauaʻi where alternative food is abundant, the difficulty in using toxicants is in establishing a delivery system or bait that would only target RRPA and avoid negative impacts on non-target animals (Avery and Shiels 2018), though prototype devices for excluding non-target birds have been tested in pilot studies on monk parakeets (Tillman 2016). The label for Starlicide® does not include parakeets, and efficacy studies would have to be completed with RRPA to expand the label. Acute toxicity tests in the closely-related budgerigar (*Melopsittacus undulatus*) indicate an LD50 of 242 mg/kg, which is about 48 times more than that needed for the Sturnidae and Icteridae families (Eisemann et al. 2003). Trials on fruit-eating, tropical birds (i.e., common mynas) have indicated sensitivity to DRC-1339, but an aversion to the bitter taste may exist that could be masked with sugar (Avery and Eisemann 2014; Feare 2010). Thus, evidence suggests Starlicide® would be less effective in the Psittacidae family. Historically, toxic insecticides (i.e., chemicals that were never registered by the US EPA as avicides) were used to control monk parakeets in South America but are now restricted (Linz et al. 2015).

Fumigation– No chemical fumigants are currently registered by the US EPA for controlling wild birds. Potential use of fumigants is limited in Kauaʻi given enclosing roost trees containing RRPA would be logistically difficult compared to situations where pest birds are roosting in human structures.

Wetting agents– Wetting-agents are used in lethal control of birds and work to destroy the insulating properties of the feathers leaving birds susceptible to hypothermia within 30 minutes of application with cold ambient temperatures <41°F (Lefebvre and Seubert 1970). Compound PA-14 Avian Stressing Agent (alkyloxy-polyethylenoxyethanol), is a non-ionic surfactant with wetting characteristics that has been used to control wintering roosts of blackbirds, but in 1992 the US EPA withdrew the registration due to cost and lack of efficacy for solving damage conflicts (Dolbeer 2017; Heisterberg et al. 1987; Stickley et al. 1986). Sodium lauryl sulfate (SLS), a surfactant used in soap products, is classified by the US EPA as a chemical of minimal risk and therefore exempt from registration under the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA Section 25b). Although not all states accept the US EPA minimum risk designation (Byrd et al. 2009; Linz et al. 2011). When used as a wetting agent, SLS requires application by USDA- APHIS-WS personnel and a product label including target species, full disclosure of the product ingredients, and directions for use (USDA-APHIS-WS 2012). Although RRPA may be more cold-sensitive than blackbirds (CABI 2018), the lack of optimal environmental conditions (i.e., coldest month average 72°F) and restrictions for use near water limits the effectiveness of this approach for use on RRPA in Kauaʻi. SLS can also negatively impact vegetation including ornamental plantings where the chemical would be applied to manage RRPA roosts.

4-aminopyridine– Avitrol® is a frightening agent with 4-aminopyridine as the active ingredient. When ingested it causes erratic flight, distress calls, and death, which may cause the remainder of the flock to leave the area. Avitrol® is registered by the US EPA for use in non-crop areas on blackbirds, sparrows, starlings, pigeons and crows; it was previously registered for corn and sunflower fields from 1970 to the 2000s (Dolbeer and Linz 2016). Avitrol® has been lab tested on RRPA in Pakistan to establish minimum dosage required to maximize distress calls, but the behavioral response in the field is not known (Bashir et al. 1981; Khan and Ahmad 1983a). Public sentiment and the inability to lure RRPA to bait piles limits the effectiveness of this approach on Kauaʻi. The label for Avitrol® does not include parakeets and efficacy studies would have to be completed on RRPA to expand the label.

Lethal Shooting

Population suppression may be feasible if a well-funded, sustained, and broad-scale control plan is established. Poaching is suspected to play a role in regulating the RRPA population near Algiers, Algeria (Bendjoudi et al. 2013), thus RRPA may be susceptible to populations declines via hunting. The smaller estimated RRPA numbers on Hawaiʻi (Big Island) requires a rapid response to prevent establishment (CABI 2018). Population reduction campaigns often fail when mortality does not exceed recruitment and when shooting mainly removes birds that would have been lost to other mortality events, such as disease or starvation (Bishop et al. 2003; Dolbeer 2017).

Opportunities to lethally reduce RRPA populations by shooting occur during foraging, loafing, nesting, and at regular flight paths. Safe, discrete methods to lethally take RRPA are needed at each of these areas (Conroy and Senar 2009). A thorough, island-wide survey of RRPA's preferred foraging, nesting, loafing, and roosting sites would assure a coordinated approach for lethal removal. In a sustained lethal campaign RRPA may change behavior to avoid risky areas after flock mates have been removed (Bunbury et al. 2019; CABI 2018). Thus, concentrated and swift action would be needed to remove the most birds prior to a behavioral change and an ongoing monitoring program would be necessary to pinpoint new locations. Rash, poorly-planned, and poorly-executed culling activities could cause setbacks and hamper an effective shooting campaign (Bunbury et al. 2019; Grarock et al. 2014).

Using the most effective firearm for a given situation will improve the number of RRPA removed, while also being sensitive to public perception. One suggestion for use in a professionally-coordinated lethal shooting campaign would be a silent and accurate CO2 operated air rifle for when the RRPA target is not moving (e.g., roosting and perching). Birds perching and exposed at foraging, loafing, nesting, and roosting sites could be taken with an air rifle. By spotlighting roosting RRPA under palm fronds or other vegetation, the rifle could be accurately sighted for shooting individual birds. Alternatively, night vision rifle scopes can be used to reduce alarm by birds and attention of onlookers. The lack of noise will reduce the flushing of other birds and thus increase the number of birds removed. RRPA are less likely to be disturbed at roosting sites on dark nights, thus moonless nights may be preferred. Air rifles are relatively low-powered, thus damage to trees will be minimal. Selection of advanced air rifles with adjustable power and light-weight pellets can reduce risk from overshooting in settings with high human density. A 12 gauge shotgun is the best tool to cull birds when in flight, such as during movement at regular flight lines or arriving at a foraging area. The use of shotguns should be limited at loafing and roosting sites to avoid behavioral shifts in site use. Extreme care should be taken in identifying the area behind the target to avoid injury and ricochet. Air-powered shotguns are commercially available but have not been evaluated for effective and humane removal of parakeets.

Foraging– Lethal removal can occur on foraging grounds including row-crop agriculture, backyard gardens, and fruit farms (Shiels et al. 2018). To increase the accuracy of removing birds and reduce damage to crops, an air rifle may be advantageous on fruit farms for birds foraging in the canopy. Shotguns may be the most effective in row-crops or when flocks are first approaching the protected area. Removing the first birds to approach a foraging area (i.e., sentinel birds) may be effective at stopping the rest of the flock. Lethal control at foraging sites could be performed year-round and specific areas targeted as preferred foods become available (e.g., invasive yellow guava) (Shiels et al. 2018).

Nesting– RRPA are loud and gregarious allowing easy identification of nesting areas, and removing breeding birds should be prioritized. After the female selects the nest site, the pair can be seen resting on branches outside of the cavity and performing mating displays (Hossain et al. 1993), providing an opportunity to remove individuals prior to or during reproduction (i.e., December to July). After the onset of nesting, males feed females and nestlings, which offers an opportunity to remove breeding males at the nest site, and thus reduce reproductive success of females (Mabb 1997a). Even if specific nests cannot be found or are inaccessible, flight lines between foraging areas and nesting colonies can be identified and reproducing male RRPA removed, which would also function to reduce nesting success.

Roosting– RRPA nighttime roosts are large, fairly-stationary concentrations and thus the most accessible for population reduction. However RRPA roosts on the Hawaiian Islands are in heavily populated urban and suburban areas and activities would be highly visible and scrutinized by the public (Avery and Shiels 2018; Butler 2003). Thus, an air rifle would be preferred due to its high accuracy, reduced noise, and reduced extraneous damage. RRPA perch and loaf before settling down in the roost, providing an opportunity to remove 1) socially high-ranking individuals and 2) breeders indicated by interactions with fledglings at certain times of the year (Mabb 1997b). It would be beneficial to collect data on the sex and age of birds removed from various tree species, location on palm, and heights, to evaluate the location of female breeders and socially-dominant birds to target for population reduction. RRPA preferentially select tall trees with larger diameters in other urban invasions (Dodaro and Battisti 2014), thus high-ranking birds may be more difficult to reach for lethal removal, but should be the focus.

Flight lines and loafing areas– Shooting locations conducive to targeting flight lines and loafing areas need to be identified through island-wide monitoring. When shooting RRPA on flight lines, shotguns would be the required firearm to effectively remove birds flying at greater distances.

Loafing areas can be identified where RRPA stop and gather prior to returning to roosts. Loafing areas provide the opportunity to target perching birds with a more precise and discrete firearm such as an air rifle.

Issuance of a nuisance wildlife control permit by the Hawai'i Department of Land and Natural Resources would be required. All permits and safety procedures should be followed when using firearms (https://web.archive.org/web/20111129064310/http://www.honolulupd.org/info/gunlaw.htm). By nature, shooting of birds involves an elevated muzzle orientation with risk of overshot and uncertain location of impact of missed shots; extreme caution should be used to ensure safe shooting operations. Although lead pellets are a widely-available, accurate, and inexpensive option, use should be avoided due to growing awareness of environmental consequences of lead contamination and poisoning of wildlife. In human-inhabited areas it is critical to use the safest shooting practices, such as only shooting birds in palms from an angle where the trunk or crown are backdrops to missed shots. Risks from overshot are increased with muzzle velocity and pellet mass; an optimum parakeet shooting campaign may involve selection of high-quality precision air rifles with adjustable power and selection of lower-mass pellets. A pellet caliber of .22 is often preferred for killing power, but smaller .177 pellets with lower mass may be a preferable safety option, particularly for small birds shot from close range.

Capture Devices

Trapping– RRPA have been successfully trapped using a modified Australian crow trap design (i.e., PAROTRAP) placed in agricultural fields in Pakistan (Bashir 1979), but have not been successful to date in the Seychelles or Kaua'i (Figure 6a) (Bunbury et al. 2019; Gaudioso et al. 2012). Remotely triggered, spring-loaded traps can also be deployed if regular feeding stations can be established (Avery and Lindsay 2016). The use of a live decoy RRPA has been shown to increase visitation to feeding stations (Peck et al. 2014). Alternative placement of traps may improve trappability in Kaua'i or the abundance of alternative food on the landscape may simply deem the traps ineffective. If placed over corn at the preferred milky stage, communication from the decoy bird may be less stressed and more inviting. Any season with reduced alternative food would also be the most productive for trapping.

Figure 6: Rose-ringed parakeets can be captured at foraging sites using a) modified Australian crow-traps baited with food that is more enticing than alternative forage available on the landscape and at roosting sites using b) long-handled hand nets run along the underside of low-hanging branches or palm fronds (Photos by USDA-APHIS Wildlife Services).

Nets– Long-handled scoop nets as currently designed are only usable for short trees or fronds that are within reach unless used with a bucket truck or other form of elevation enhancement (Figure 6b). Traditional capture of red-billed quelea (*Quelea quelea*) included using hand nets to capture large numbers of birds at tree roosts in Africa (Mulliè 2000). Long-handled nets have also been developed for removal of monk parakeets from nests (Avery and Lindsay 2016). After establishing flight lines, elevated mist nets may be able to capture birds upon arrival or departure from roost sites (Avery and Shiels 2018). Cannon nets powered by gun powder or bungee can project a net over a flock of ground feeding birds (Schemnitz et al. 2009). The use of cannon nets to capture birds in tree roosts (e.g., royal palms) is limited given the height and structure of the trees. Unmanned aircraft systems (UAS; drones) designed to shoot nets may allow deployment over tall trees after RRPA settle into their nighttime roosts. Such configurations have been developed for capture of rogue drones, but have not been developed for animal capture. Safe recovery of birds from nets deployed in such a fashion should be considered, due to opportunity for escape, stress, injury, and death from poor netting practices.

Although live capture followed by humane destruction (euthanasia) or redistribution are likely to be preferred alternatives by some members of society, initial indications are that trapping is not likely to be a cost-effective component of a population reduction strategy due to unsuccessful trapping attempts on Kaua'i and required labor. However, plausible alternative trapping strategies should be considered for further evaluation. Once captured, there are no reasonable prospects for a non-lethal disposal of live birds. From an animal welfare perspective, the stress of capture and transportation for euthanasia may far exceed the stress of being immediately dispatched by methods that may be naively considered less 'humane' on face value (e.g., shooting).

Fertility Control

Contraceptives– Reproductive inhibition is often cited for pest scenarios in urban situations where conventional control is not feasible and culling of charismatic animals is not viewed favorably by the public (Fagerstone et al. 2010). In the US two compounds have been tested as avian contraceptives: DiazaCon (20,25 diazacholesterol dihydrochloride) and Nicarbazin. Although Nicarbazin is non-toxic, reversible, and cleared from the body after 48 hours, the disadvantage is that target birds need to ingest the compound daily prior to and during egg laying (Avery 2014). DiazaCon lasts an entire breeding season after a limited 10-day exposure period (Yoder et al. 2007). DiazaCon has been tested in captive RRPA and was shown to reduce fertility by reducing blood cholesterol and cholesterol-dependent hormones to disrupt egg production (Lambert et al. 2010). Lambert et al. (2010) indicated that 10 days of dosing at 18 mg kg-1 were sufficient to reduce fertility (i.e., same number of eggs laid but fewer fertile) for the entire breeding season. RRPA were also shown to incubate infertile eggs up to 60 days (3x the normal incubation period), which would limit renesting and further reduce reproductive output (Lambert et al. 2010). Although fertility control appears promising, a suitable formulation and species-specific application methods are needed in the field. Even if managers are successful in establishing bait stations that could only be accessed by RRPA and limit non-target exposure (Tillman 2016), the method would require an ability to condition wild RRPA to feed at these stations (Avery and Shiels 2018; Peck et al. 2014). The design and distribution of such bait stations may work for small populations of urban parakeets but remain questionable on Kaua'i where birds have dispersed to into rural settings with abundant alternative food sources year round (Lambert et al. 2010). The labels for Ornitrol® (DiazaCon) and OvoControl® (Nicarbazin) do not include parakeets, and additional efficacy studies would have to be completed to expand the label.

Egg destruction– Destroying, removing, or addling eggs (e.g., oiling, puncturing, or shaking) is a way to reduce reproductive success of birds (Beaumont et al. 2018; DeVault et al. 2014; Ridgway et al. 2012). Egg oiling with corn oil is allowed by the US EPA under a (FIFRA) 25b exemption (Fagerstone et al. 2002). Nest destruction is limited to the breeding season, but prolonged nest occupancy (>10 weeks) of RRPA gives sufficient time to find nests. Addling of eggs is the preferred method of nest destruction as birds continue incubation, thus delay renesting and continue occupation of the nest. RRPA are not known to renest unless the entire clutch is lost. It has been surmised that species with long nestling periods are especially prone to trapping for the pet trade (Cassey et al. 2004), thus removal of nestlings will also reduce reproduction if the nest is found during brooding. On Kaua'i the endeavor would be labor-intensive and logistically difficult to find enough nests to impact population numbers, especially given RRPA are cavity nesters that prefer the highest holes in tall trees. Nest management is more likely to be successful when RRPA occupy nest boxes or other easily accessible nest cavities such as those found in urban settings (Grandi et al. 2018). Nest boxes could be used as traps to remove breeding birds or to oil eggs to reduce reproductive success (Tidemann et al. 2011), but the effectiveness of lethal control at the nest is limited on Kaua'i by the abundance of natural cavities, thus it is reasonable to believe that artificial nest boxes may have limited attraction, but is worth further evaluation.

Nest destruction– RRPA have shown preferences for particular trees (Czajka et al. 2011). The preferred nesting trees need to be identified in Hawai'i for management actions at the nest site. In Italy, an exotic ornamental tree, *Cedrus libanotica*, was the preferred nesting tree, thus management of this tree was proposed to limit RRPA breeding (Dodaro and Battisti 2014). The destruction of mature, invasive albizia trees on Kaua'i, a tree providing abundant nest cavities, could destroy established breeding colonies. If the removal of trees with abundant RRPA nesting cavities is not feasible, another approach would be to modify the cavity to deem it unusable by RRPA (Orchan et al. 2013). Nest removal was considered less efficient for reducing populations of monk parakeets, which is informative in that these nests are much easier to locate and the colonial nature would destroy many nests at once (Conroy and Senar 2009). Albeit, colonies of monk parakeets were not limited in habitat to rebuild nests, whereas removing invasive trees with abundant cavities would limit RRPA reproduction opportunities.

Reproductive inhibition can play an important role in a population reduction program by slowing the recruitment of new individuals into the population. Because of the difficulties associated with locating and accessing RRPA nest cavities, egg and nest destruction are not likely to be fruitful avenues for management action. Barriers to effective chemical fertility control (contraception) include lack of products for permanent sterilization, long lifespans of parakeets, risks to nontarget bird species, and regulatory burdens. However, some existing products may warrant further investigation, and evaluation of potential nontarget-exclusion feeder devices may be a fruitful avenue of research (Tillman 2016). Fertility control may be a component of a multifaceted approach where its application may be the only acceptable method (e.g. in heavily-inhabited areas, where risks to native nontargets are low). Despite challenges, we consider chemical fertility control to be a possible avenue for further research.

Exclusion Techniques

Physical Exclusion

Netting– Complete physical exclusion via netting can be used to protect agricultural crops and roosting trees (Figure 7a-b). Hawaiian farmers report using netting to exclude birds from sensitive crops but also indicate the practice is prohibitively labor-intensive and expensive (Koopman and Pitt 2007). The practice of netting is practiced by large seed companies (e.g., Monsanto, Pioneer) with thousands of dollars spent each year to manage bird damage (Koopman and Pitt 2007). Reddy and Gurumurthy (2003) found netting to exclude RRPA increased yield compared to plots with frightening devices.

Overhead lines and wires– Partial physical exclusion via overhead wires and lines can be used to protect agricultural crops. Overhead lines and wires have been shown to reduce visitation by birds to fish ponds, row-crops, hay bales, and orchard trees (Blokpoel and Tessier 1984; Dolbeer et al. 1988; McNamara et al. 2002; Pochop et al. 1990). The installation (i.e., wire pattern and spacing) needs to be species-specific to increase functionality in that the wires must be close enough to deter birds from passing through but wide enough to limit cost and maintenance. In the case of fruit trees a teepee design starting above the tree and running to the ground is suggested (Bishop et al. 2003). Overhead lines and wires are often used for larger species that require long uninterrupted landing and takeoff space (i.e., waterfowl over ponds); being maneuverable fliers and agile climbers, RRPA do not have characteristics of birds typically excluded by these techniques. Overhead lines and wire have not been tested on RRPA.

Crop camouflage– Bird damage to corn is reduced after placing bags over ears post-fertilization, and thus is a practice that could

Figure 7: Rose-ringed parakeet damage can be reduced by completely covering a) fruit trees (Photo by Marty McCarthy) or b) row crops (Photo by Dan Dennison, HI DLNR) or at a smaller scale the individual fruiting bodies, examples including c) paper bags over fertilized corn (Photo by Hannah Neuenschwander), d) wire mesh over large fruits, and e) plastic containers or screen bags over fruit bunches (https://www.houzz.com/discussions/lychee-trees-update-2-dsvw-vd~2182466).

be continued and tried on other crops (Compton 2004). RRPA are strong enough to tear the paper, thus the bag may act to camouflage the fruit. The effect is bolstered by RRPA having alternative sources of food, otherwise bags would not be effective exclusionary devices. Seed companies on Kaua'i bag crops as a part of their fertilization process and have indicated reduced RRPA damage on the bagged corn ears. Individual fruits or fruit bunches on orchard trees can be covered by a sturdy mesh bag or enclosed by an aerated plastic fruit container (Figure 7c-e).

Auditory Exclusion

Sonic net– A "sonic net" is a sound technology proven effective at long-term displacement of pest birds from airports and food sources (Mahjoub et al. 2015; Swaddle et al. 2015). Sonic nets produce a highly directional, contained sound that masks communication for birds (2-10 kHz at 80 dB SPL). When birds cannot communicate or hear predators, their perception of predation risk increases, which may result in reduced foraging or complete abandonment of foraging grounds (Mahjoub et al. 2015; Swaddle et al. 2015). The deterrence response is enhanced in situations where there are real predatory threats as well as alternative food resources. In previous studies, birds did not decrease their sensitivity to sonic nets through habituation (Swaddle et al. 2015). The sonic net can be used in exurban environments due to directional speakers, but is not feasible in urban roosts given the noise produced is audible to humans and RRPA freely use noisy urban areas. Sonic nets have not been tested on RRPA.

Repellents

Tactile Repellents

Anti-perching tools– Anti-perching tools create an environment to discourage perching or roosting on structures. Physical devices to deter perching include strips of sharp spikes, wire barriers, unstable system of coils, electrified cables, and gels to create an uncomfortable surface (Andelt and Burnham 1993; Bishop et al. 2003; Gorenzel and Salmon 2008). Some tactile repellents are sticky pastes while others use a chemical substance (e.g., polybutenes) that induces a negative reaction when absorbed through the foot. These types of deterrent devices have been effective for controlling larger-bodied birds such as pigeons (*Columba livia*) inside human structures and raptors on antennas, but smaller birds that use less space to perch are capable of avoiding the substance (Bishop et al. 2003). Although anti-perching tools are weather resistant, the use on roosting trees is not practical given the logistics of installing the devices and potential damage to the roost tree.

Water mist and spray devices– Use of water spray devices have been used in various bird damage management situations and can function to reduce visibility of the resource to be protected or as a reflexive withdraw due to direct water pressure or wet feathers impacting functionality (Bishop et al. 2003; Kevan 1992; Littauer et al. 1997). For example, a sprinkler activated by a motion-detector can be set-up to startle birds with a stream of water (Heidenreich 2007). RRPA were shown to be susceptible to fog (Bendjoudi et al. 2013; Temara and Arnhem 1996), thus continually wetting feathers, such as through a mist system installed under palm fronds on RRPA roost trees may deter birds if turned on just prior to roosting. Applying a high pressure water stream just prior to roosting can disperse birds from the target tree, but this method has not been evaluated in the literature aside from being used to remove swallow (Hirundinidae) nests during nest building (Gorenzel and Salmon 1994).

Chemical repellents

Compared to tactile repellents, chemical repellents are intended to prevent ingestion of treated items rather than exclusion from perching or roosting sites. The development of effective chemical repellents has a long history in North America but few commercial repellents are registered for use with the US EPA (Werner and Avery 2017). Numerous insecticides and fungicides have been tested over the years with varying effectiveness, and limitations due to environmental impact and food tolerance requirements for human safety when applied near harvest (Avery 2003; Linz et al. 2011; Werner and Avery 2017). For example, methiocarb has been tested as an avian repellent for RRPA and is still used in some countries (Hussain et al. 1992), but it is no longer registered by the US EPA due to lack of data and cost to support continued use (i.e., product chemistry, residue chemistry, ecological effects, environmental fate, toxicology and occupational/residential exposure) (Eisemann et al. 2011). Natural plant derivatives such as mint, caffeine, cinnamon have also been tested but a lack of economic incentives and variable effectiveness causes a paucity of commercial products (Avery and Decker 1992; Avery et al. 1996a; Avery et al. 2005). Flock Buster® (i.e., lemongrass oil, garlic oil, clove oil, peppermint oil, rosemary oil, thyme oil, and black pepper) is a commercial product currently available, but when tested on blackbirds in the lab it showed a <50% repellency (Linz et al. 2011). The two main ingredients in avian repellents currently registered by the US EPA are methyl anthranilate (MA) and anthraquinone (AQ).

Various products containing methyl anthranilate are registered by the state of Hawaiʻi for use in a variety of pest situations. No anthraquinone products are currently labeled but if considered necessary for Kauaʻi, a special local needs registration would need to be obtained under Federal Insecticide, Fungicide, and Rodenticide ACT (FIFRA) Section 24(c), which must also be approved by the State of Hawaiʻi Department of Agriculture, Pesticides Branch. Use of pesticides may be viewed unfavorably by the public due to perceived environmental risks and public affection for charismatic bird species. Hawaiʻi may be a challenging environment to achieve social license for avicide or repellent use.

Methyl anthranilate– Methyl anthranilate (methyl 2-aminobenzoate) is a human-food additive that is aversive to birds when it acts as an irritant on the trigeminal nerve (Mason et al. 1989). Although there are few scientific evaluations of its effectiveness, MA has been used on cereal grains, stone fruits, pome fruit, berries, small fruit, and turf (Avery 1992; Avery et al. 1996b; Linz et al. 2011; Werner et al. 2005). Aerosolized treatment is stated to be more effective than direct application to the resource (Stevens and Clark 1998; Vogt 1997) and is a potential method to influence flight lines (Engeman et al. 2002). Monk parakeets have exhibited behaviors that indicate sensitivity to aerosolized MA, but application did not cause parakeets to abandon an established nest (Avery et al. 2006). Systems that deliver MA in a fog are not recommended for areas with human exposure due to the chemical irritant having an adverse smell and agricultural producers may not want to apply to fruit crops due to taste. Methyl anthranilate (i.e., Bird Shield, Avian Control™ and RejeX-It™ Fog Force AR20) is registered by the US EPA with label specifications for a variety of pest birds and habitats

Anthraquinone– Although the mode of action is unknown, 9,10 anthraquinone (AQ) is a secondary repellent with a post-digestive antifeeding effect on a variety of bird species; the negative effects of an initial feeding induce aversion to subsequent feedings (Avery et al. 1997; DeLiberto and Werner 2016). AV-1011® (rice) and Avipel® (corn) are restricted-use pesticides for use on seeds and applied as a coating prior to planting and is registered as a Section 24(c) Special Local Need (SLN) Registration. The potential use on Kaua'i is limited in that RRPA damage to planted seeds or seedlings has not been reported. Flight Control® is an AQ-product registered by the US EPA for use on turf and Airepel® for use on structures as a roost deterrent. A US EPA registration for application near harvest is not available or suitable due to food tolerance restrictions and limitations in effective field application (Kaiser 2019). Thus, an AQ-based repellent is not available for ripening crops or fruit intended for the food stream.

Frightening Devices

Novel stimuli as deterrents may invoke a fear response in birds (Shivashankar and Subramanya 2008). Thus, frightening devices are intended to offer temporary protection from wildlife damage on a scale of days to weeks and not meant as a long-term solution (Avery and Werner 2017). The success of frightening devices is limited by bird behaviors such as strong fidelity to established feeding areas and habituation to non-random noise as well as the extent of effectiveness in space and time, immobility, and labor intensity of the device (Gilsdorf et al. 2002; Linz and Hanzel 2015). In order to get the best results from scaring devices, the following guidelines should be followed: 1) early implementation prior to establishment of feeding, 2) random presentation of sounds or visuals, 3) use of a variety of sounds and visuals, and 4) auditory and visual deterrents used in combination or reinforced by a negative stimulus such as shooting (Cleary and Dolbeer 2005; Fitzgerald 2013; Linz et al. 2011). However, limited scientific evidence is available for supporting lethal reinforcement and differences may exist depending on species (Washburn et al. 2006; Baxter and Allan 2008; Seamans et al. 2013). Those wishing to deter RRPA should do so with an understanding that extensive effort must be made to constantly create a novel environment by switching, combining, and moving the devices to maintain novelty.

Unfortunately, many frightening devices on the market have not been objectively tested at the field scale and when tested difficulties arise with acquiring appropriate replication and controls (Avery and Werner 2017; Bomford and O'Brien 1990). From a crop producer's standpoint, the perception of impacts on profits and effectiveness of scare devices ranges from ineffective to somewhat effective (Anderson et al. 2013). Blanket statements about device effectiveness are not feasible given the unique and unpredictable nature of wildlife damage that varies with pest species, protected resource, and landscape scenario.

As global invaders, some devices have been tested on RRPA or closely-related species (Psittacidae). Reflecting ribbons, streamers, flagging, exploders, and other combined scaring devices (i.e., reflecting mirrors, hawk eyes and dead effigies) were used in maize and sunflower fields in Pakistan (Ahmad et al. 2012). Distress calls, predator effigies, reflecting mirrors, gas exploders, and reflecting ribbons were tested in mango, citrus, and guava orchards in Pakistan (Khan et al. 2011). Novel stimuli including streamers, silver plates, and plastic bags attached to individual plants were used to protect sunflowers in India (Shivashankar and Subramanya 2008). Bioacoustics were used in Pakistan to deter RRPA from crop fields (Mahesh et al. 2017). For devices that have not been tested on RRPA, effectiveness requires inferences to be drawn from other species. The few field tests conducted on scare devices are limited to a few species and in environments that are not necessarily similar to Kauaʻi.

Auditory

Bioacoustics– Bioacoustics include natural sounds such as predators (e.g., barking dogs, raptor calls, human noise) and avian distress and alarm calls (Gorenzel and Salmon 2008). Distress calls have been used for decades and some research is available for a limited number of species (Brough 1969). Flocking birds are likely to be susceptible to natural alarm and distress calls due to reliance on flock mates for information. When natural avian vocalizations are used habituation may take longer because anti-predator communication of birds remains relevant. Bioacoustics are species-specific and can even be specific to a location or social group. Broadcast alarm stimuli were tested in apple orchards and shown to reduce activity of crimson rosellas (*Platycercus elegans*), an Australian parrot species (Ribot et al. 2011). Distress calls have been successfully used to disperse avian roosts including those of various Corvids (Avery et al. 2008; Delwiche et al. 2005) and European starlings (*Sturnus vulgaris*). Studies evaluating effectiveness of distress calls, in combination with visual scare devices, have shown effectiveness at protecting fruit farms (e.g., grapes, cherries and blueberries) from European starlings, American robins (*Turdus migratorius*), and house finches (*Carpodacus mexicanus*) (Berge et al. 2007). Gulls (*Larus* spp. and *Chroicocephalus ridibundus*) have also been successfully dispersed from landfills using distress calls in addition to shooting and falconry (Cook et al. 2008). Although these studies have found success, the result can be short-lived and a continual rotation and variety in control tools (e.g., shooting and effigies) is necessary to prolong effectiveness (Cook et al. 2008; Heidenreich 2007).

RRPA have been temporarily deterred from crops in India using species-specific alarm calls and predator calls (Mahesh et al. 2017). Predator sounds were broadcast in orchards in Pakistan and visits by RRPA and concomitant damage was less than control orchards (Khan et al. 2011). In Hawaii, RRPA may habituate more quickly to bioacoustics when natural threats are not prevalent due to a limited number of natural predators. Different bird species respond differently to distress calls. For example, gulls will visually confirm the danger by flying toward the distress call; thus additional pyrotechnics or shooting is needed for reinforcing the distress call (Conover 1994). Understanding RRPA response to alarm and distress calls will improve the effectiveness of biosonic devices. Distress calls may draw in other RRPA resulting the opposite of the desired effect, but may provide opportunity for lethal removal.

Gas cannons– Propane cannons produce a loud, directional blast by the ignition of propane gas and are among the most popular avian scaring devices (Bomford and O'Brien 1990). The mode of action is to create a random, loud and unexpected noise (130 dB) that resembles a shotgun blast to elicit an escape response (Harris and Davis 1998). The advantages of gas exploders are initial affordability, inexpensive operation and maintenance, and portability. The effectiveness of propane cannon increases when raised off the ground, allowed to rotate for multi-directionality, and moved to increase range and decrease habituation (Bishop et al. 2003; Harris and Davis 1998). The disadvantages of auditory scare devices include fire hazards, habituation without lethal reinforcement, limited range of effectiveness without moving the device, reduced range in adverse weather, and the most importantly for Hawaii, the inability to use in urban and semi-urban areas due to noise complaints (Linz et al. 2011; Washburn et al. 2006). Artificial aural deterrents are widely marketed, but any effect is likely short-lived due to habituation and limited in range with suggestions of one cannon per 2-3 acres (Avery and Werner 2017; Cummings et al. 1986) and protection provided within 60-120 meters (Cardinell and Hayne 1945).

Pyrotechnics– Pyrotechnics include a variety of noise-producing cartridges that produce flashes of light and loud bangs (160 dB) and whistles (e.g., screamers, bangers, shell crackers, CAPA launchers) (Garner 1978). The advantage of pyrotechnics include the ability to have directional control of the tool. Any effect is likely short-lived due to habituation and a limited range of 45-90 meters (Bishop et al. 2003); the tool is also labor intensive in that it requires an operator. Further limitations of pyrotechnics include the inability to use in urban areas and the potential fire hazard (Harris and Davis 1998).

Vortex Ring Accelerator Deterrent (VRAD)– The VRAD propels exhaust through a vortex ring generator via combustion which then passes through an accelerator creating a high-velocity vortex ring that is propelled up to 6 miles at speeds up to 200 mph. The action of the vortex ring deters birds through auditory as well as an irritating, non-lethal physical concussion. The cost effectiveness has not been scientifically evaluated, but has been used to keep waterfowl out of mine tailings and reduce avian damage on fruit farms (https://flockfree.com). The sound intensity produced makes this an unlikely management method for RRPA at the urban roosting sites or exurban agricultural sites. This technology is experimental with large and costly equipment.

Ultrasonic sound– Ultrasonic devices project sound at greater than 20 kHz frequency and the effectiveness for bird species will depend on their sensitivity to sound frequencies (Beason 2004). For example, the upper limit of sensitivity for many birds is <10 kHz (Dooling 1982; Erickson et al. 1992), although prolonged exposure to ultrasonic sound waves may result in discomfort or hearing loss (Lawton 2001). Devices emitting ultrasonic sound have been tested on birds in Nigeria with assertions of deterrence (Ezeonu et al. 2012). To date, ultrasonic deterrent devices have not been tested on any psittacine species. Although ultrasonic sound is not perceptible to humans, ultrasonic devices to deter RRPA is not a suggested management avenue due to RRPA likely lacking overt sensitivity to ultrasonic frequencies, limited evidence of effectiveness on other species, and potential risk of prolonged exposure. For example, the closely-related, budgerigar (*Melopsittacus undulatus*), have upper limit of 14 kHz sensitivity (Knecht 1939). Several products targeted at the consumer market are available; there is no substantial evidence that they provide any true deterrent effect.

Visual

Balloons– Inflated balloons suspended above the resource and allowed to move freely in the wind have been used to protect crops and deter roosting in a variety of species. Numerous field trials indicate the influence of balloons are species-specific, and any effect is short-lived (Bishop et al. 2003; Greer and O'Connor 1994; McLennan et al. 1995). For example, McLennan et al. (1995) used eye-spot balloon in New Zealand vineyards and were able to reduce activity of most birds except song thrushes. Mott (1985) realized an 82% reduction in bird numbers when using helium-filled balloon in blackbird roosts. In Japan, researchers successfully tested the impact of large eye-spot balloons for protecting fruit orchards from white eyed starlings (*Spodiospar cineraceus*) for two weeks (Shirota et al. 1983). The same effect was not seen when eye-spot balloons were tested on grackles (*Quiscula* spp.) depredating citrus in lab and field trials (Avery et al. 1988; Tipton et al. 1989). The size, number, and balloon design may increase effectiveness, and care must be taken to limit entanglement in vegetation, especially in windy environments. The response of RRPA to eye-spot balloons has not been evaluated.

Hawk kites– Hawk kites are suspended predator models that move in the wind to improve upon stationary predator effigies. The fear factor and subsequent habituation varies by species with the effectiveness being the greatest directly below the model (Conover 1983, 1984; Hothem and DeHaven 1982; Seamans et al. 2002). The number of kites for effective bird deterrence was estimated at 1 kite/ha (Marsh et al. 1991; Seamans et al. 2002). The response of RRPA to hawk kites has not been tested.

Reflective tape– Reflective tape (1 cm wide and 0.25 cm thick) is used by twisting parallel lines of the shiny tape (red and white) between poles over the crop. The reflectance, physical barrier, and sound of wind through the lines elicits a fear response, but once again the response and subsequent habituation varies by species and environment (Bruggers et al. 1986; Conover and Dolbeer 1989; Dolbeer et al. 1986; McKay and Parrott 2002; Summers and Hillman 1990; Tobin et al. 1988). Large gaps allow access by pest birds, thus complete coverage, narrow spacing, and routine maintenance of the tape influences effectiveness, but increases cost (Bishop et al. 2003). Reflecting ribbons and silver plates attached to individual plants were used in India to limit RRPA damage in sunflower (Basappa 2004; Shivashankar and Subramanya 2008), but the technique has not been evaluated at roost sites.

Streamers and flags– Suspended plastic or cloth that moves in the wind and placed throughout the field is an inexpensive way to reduce crop predation by birds. Flags have been successfully used against red-billed quelea in rice plots, blackbirds in corn, snow geese (*Chen caerulescens*) in winter wheat, and gulls (*Larus* spp.) in loafing areas but not nesting colonies (Belant and Ickes 1997; Cardinell and Hayne 1945; Manikowski and Billiet 1984; Mason et al. 1993). Gorenzel and Salmon (1992) tested streamers to disperse Corvids from roost trees with Mylar tape (0.6-0.9 m) being effective, but limitations include difficulty in applying to tall trees and birds moving to untreated trees. Shivashankar and Subramanya (2008) found plastic bags attached to the sunflower reduced RRPA damage.

Dead bird effigies– Dead bird effigies, often taxidermied or using real feathers, have been used to successfully disperse vultures and crows from roosting sites (Avery et al. 2002b; Avery et al. 2008; Seamans 2004; Tillman et al. 2002). Monk parakeets and Canada geese (*Branta canadensis*) did not respond to dead effigies of their respective species when displayed at established nest sites (Avery et al. 2002a; Seamans and Bernhardt 2004). The gregarious, social nature of RRPA suggests the dead parakeet effigies may elicit a response in both foraging and roosting situations and has potential as a fairly inexpensive deterrent. Albeit, roosting RRPA may simply move to a nearby tree.

Scarecrows– Human scarers and scarecrows have been used to protect agricultural resources for millennia (Warnes 2016). Modifications of modern scarecrows include devices that try to mimic human predators with appearance and movements (Marsh et al. 1992; Stickley Jr et al. 1995). Combining frightening techniques, such as adding bioacoustics or artificial sound, is also thought to prolong habituation and enhance effectiveness (DeHaven 1971). The addition of loud, unpredictable sounds coupled with a pop-up scarecrow can increase effectiveness, but most birds are able to habituate or are not phased if deployed in established foraging grounds (Cummings et al. 1986). Intelligent wildlife species are also known to sensitize to the appearance of human harassers or even their vehicles (Grant et al. 2011). This behavior is possible in RRPA and can either reduce the effectiveness of human harassers or can be capitalized on by modeling scarecrows after actual threats.

Falconry, native predators, and raptor models– Birds quickly habituate to stationary, plastic models of predators, thus encouraging natural predators is a technique that capitalizes on natural predator-prey systems (Lindell et al. 2018). Passive encouragement in the form of nest boxes and perch space for owls and raptors have been used to protect fruit farms (Jedlicka et al. 2011; Kross et al. 2016; Kross et al. 2012). The use of attracting more predators is limited in Hawai'i given the limited native raptor species and not wanting to promote invasive predators. For example, barn owls (*Tyto alba*) are a predator that is used to control agricultural pests, but in Hawai'i are considered pest themselves as they prey on seabird colonies (Raine et al. 2017). To allow for a more a controlled predator method, falconry has been used, although the high cost and temporary nature of the response are major limitations (Erickson et al. 1990).

Manned aircraft and unmanned aircraft systems (UAS)– Manned aircraft in the form of fixed-wing airplanes and helicopters have been used to haze blackbirds in sunflower and rice fields but aside from eliciting a flight response the efficacy in reducing crop damage is unknown (Cummings et al. 2005; Handegard 1988). Helicopter flights performed at low altitudes over roosts caused the mixed blackbird flocks to disperse but was dependent on weather conditions (Mott 1983). The limitations of manned aircraft is the cost and more importantly the risk to human safety (DeHaven 1971; Linz et al. 2011).

Unmanned aircraft systems (UAS) are a dynamic hazing device that reduces human safety risks and operation costs while also overcoming mobility limitations of stationary devices (Klug 2017). Remote-controlled aircraft have been used as hazing tools but the skill required to fly theses platforms limited use (Solman 1981). Recent UAS technology allows easy to operate platforms and the potential for autonomous flight completely removes the need for a human operator (Grimm et al. 2012). The efficacy of UAS as hazing tools depends on the species-specific response to UAS form and flight dynamics. Avian responses to UAS have been tested on blackbirds and geese, but RRPA or related species have not been evaluated (Blackwell et al. 2012; Doppler et al. 2015; Klug 2017).

Intense light and lasers– Intense light holds the opportunity to be aversive to birds (Lustick 1973), but can also be an attractant (Gorenzel and Salmon 2008). The use of flashing, rotating, strobe, barricade and flood lights have all been proposed tools to deter birds (Gorenzel and Salmon 2008). In Hawai'i the use of bright lights to illuminate roost trees would have to be balanced with the negative impacts of light pollution on native species and the likelihood that RRPA would behaviorally adjust to bright lights. Search lights are needed to locate roosting RRPA for implementation of other management tools.

Light in the form of lasers has been a promising avenue and has been widely marketed as a bird deterrent (Blackwell et al. 2002; Glahn et al. 2000; Gorenzel et al. 2002). The closely-related monk parakeet has been shown to be sensitive to red lasers (50 mm aperture, 650 nm, 50mW [class3 IIIb]), and although researchers were able to reduce the number of birds at the established nest colony the overall number of birds in the areas was not reduced and a core number of birds remained (Avery et al. 2002a). The selection of the laser type and the conditions in which it is used need to be evaluated through an understanding of the visual capability of the pest bird (Homan et al. 2010). Handheld lasers are currently used by property owners to deter RRPA from roosting trees (M. Martin, pers. comm.) and automated models are available to spatially and temporally confine laser beams and reduce labor. When used properly, lasers can be a safe and silent treatment to temporarily disperse birds. All permits and safety procedures should be followed when using lasers. Powerful lasers may cause eye damage to humans or habituated birds that do not disperse if oriented directly at the eyes. Care should be taken to avoid orienting lasers toward aircraft given inadvertent laser strikes on aircraft could pose serious safety risks; the Federal Aviation Administration will pursue civil and criminal penalties against those who purposely aim lasers at aircraft (https://www.faa.gov/about/initiatives/lasers/).

Habitat Modification

Vegetation Management

Roosting and loafing site management– The removal or modification of roost structures has been successfully implemented for other pest birds. In North Dakota, cattail roosts were modified to disperse large flocks of blackbirds (Linz and Homan 2011). Tree rows next to row-crops are often used by RRPA as perching and loafing sites in Pakistan (Khan et al. 2004). When possible regularly used loafing sites should be removed to reduce habitat suitability surrounding the crop fields, given tree rows next to crops are routinely used (Shivashankar and Subramanya 2008). The removal of invasive albizia trees functions to remove potential roosting and nesting habitat, and is especially important given the number of cavities available for nesting in mature stands. In Louisiana, trees were trimmed to a third of the canopy to reduce the presence of an urban wintering blackbird roost (Good and Johnson 1976). Trimming royal palms and other roosting trees may reduce the roost size in a tree but is not advised by arborists, given excessive trimming will likely weaken the tree and is aesthetically unappealing. Using alternative landscaping and incorporating native plants such as loulu palm will reduce habitat suitability for RRPA.

Crop Management and Alternative Food

Crop siting– Hawai‘i has a range of farm sizes ranging from large (800-1,200 ha) to small farms (1-12 ha). Historically, the dominant crops were sugarcane and pineapple (*Ananas comosus*) grown on large plantations, whereas a diversity of crops are now grown on numerous small acreages, leading to increased conflict between birds and agriculture (Koopman and Pitt 2007). Although not feasible in all crops (i.e., orchards), the location and size of crop fields may impact damage from RRPA. Mukherjee et al. (2000) indicated that crop damage was more severe at edges of sunflower fields, thus suggested using larger plots or reducing the amount of space between plots to limit the preferred foraging spots where RRPA have space to maneuver and be vigilant to threats (Subramanya 1994). Although, smaller plots allow better access for deployment of control tools (Linz et al. 2011). The spatial configuration of crop damage by RRPA on Kaua‘i is not known, and small, diversified plots may be at greater risk because the RRPA can meet all of their nutritional needs in one location as a different crop is continually ripening throughout the year. In other bird pest situations, it is suggested to synchronizing planting time to eliminate early and late-maturing crops in the same locality (Linz et al. 2011).

Crop availability– Camouflaging maturing corn cobs is a traditional method of reducing bird damage in Africa and wrapping cobs with bags or maize leaves has been shown to reduce damage in small plots (Conover 1987; Ruelle and Bruggers 1982). The reduction in damage by RRPA is likely due to the cobs escaping detection by foraging RRPA, but could also be due to difficulty of tearing through bags, the birds being unable to preferentially select the best cobs, and the availability of alternative food resources reducing pressure on the wrapped plots (Dhindsa et al. 1992; Dolbeer et al. 1982). Although potentially effective this a labor-intensive practice cannot be done on a large scale, although in one day six people can cover all cobs in one acre at 120 ears/hour, which may be more labor intensive than continuous hazing for the duration of crop vulnerability (Conover 1987; Dhindsa et al. 1992). The practice may increase insects and mold as shown in cloth-covered sorghum, but likely depends on environment and timing of management (Dhindsa et al. 1992). It has been noted on Kaua‘i that damage inflicted by RRPA on corn is reduced after placement of fertilization bags over ears. Thus, this method of camouflaging crops may be effective method to consider in other commodities.

Advancing the harvest date reduces the damage window, thus reduces yield loss from bird depredations (Linz et al. 2011). In cereal crops, such as sunflower, the harvest date can be advanced two weeks by using a herbicide to desiccate the crop without compromising yield or oil content (Linz et al. 2011). In fruit crops harvest date can be advanced to reduce yield loss in hard hit areas.

Decoy crops and alternative food– The availability of alternative food resources impacts the effectiveness of damage management tools (Mahesh et al. 2017). Trap crops have been suggested as a means to prevent depredation on higher-valued crops for a variety of pest species (Cummings et al. 1987; Hagy et al. 2008; Kubasiewicz et al. 2016), and has been suggested for deterring RRPA damage (Iqbal et al. 2001). Fields positioned closest to the roosts may be best suited for decoy crops (Khan et al. 2006), but in some situations the decoy crop should be positioned close to the target field and birds feeding in the decoy crops not be harassed but allowed to feed. Sorghum and pearl millet are potential decoy crops to use to entice RRPA away from high value commodity crops (Dhindsa et al. 1992; Saini and Dhindsa 1993; Saini et al. 1994; Simwat and Sidhu 1974). RRPA preference for ground nut kernels (i.e., peanuts; *Archis hypogaea*) over cereal grains have also been shown in lab settings (Simwat and Sidhu 1974). The use of decoy crops are better suited to some types of agriculture and on Kaua‘i the use of decoy crops will likely be more cost-effective and feasible where tillable land is available and alternative food is enticing. Additionally, alternative food sources can be provided by delaying the disking of harvested grain fields (Linz et al. 2011), or in the case of seed companies on Kaua‘i, delaying destruction of unharvested plants.

Invasive parakeets use backyard bird feeders that may supplement populations when other food is not available (Butler 2003; Clergeau and Vergnes 2011; Garrett et al. 1997; Hart and Downs 2014; Lambert et al. 2010; Owre 1973). Clarification is needed if RRPA use bird feeders in Hawai'i (confirmed on O'ahu) and if the practice can be stemmed or if availability of feeders to RRPA could be reduced. Although, if RRPA regularly use bird feeders, a RRPA-specific feeder could be validated and used for the distribution of contraceptives, avicides, trapping, or shooting (Lambert et al. 2017; Tillman 2016).

Human Dimensions

Preferences for tools to decrease wildlife damage are often related to sociopsychological and sociodemographic factors. In Argentina, attitudes about monk parakeets and perception of damage and knowledge of effectiveness were important in management preferences (i.e., lethal vs. nonlethal alternatives) (Canavelli et al. 2013). Although education programs work to inform the public about invasive species, sometimes attitudes do not change as a result of educational intervention (Braun et al. 2010). Thus eradication programs targeted at charismatic species can face public opposition (Blackburn et al. 2010), especially in urban areas, where colorful gregarious birds are a novelty (Burger and Gochfeld 2009; Cassey et al. 2015). The longer a species is present, the more difficult eradication campaigns are as public attachment increases (Decocq 2010; Papworth et al. 2009). Emphasis should be placed on a campaign informing the public about RRPA, while being sensitive to interactions with animal rights groups and exploring positive collaborations if possible (Perry and Perry 2008).

Conclusions

An effective management plan is needed to identify adaptive strategies for informed and effective implementation of lethal and non-lethal methods to reduce damages cause by RRPA. Recommended methods and tools need to be appropriate to the context and acceptable to the social climate on Hawaii.

- Deterrence (habitat modification, exclusion, and frightening devices) is an appropriate objective for individual stakeholders looking to protect their resources. In most cases, the effects of these methods are short-lived and require constant human perseverance in continually moving and combining devices to create environments that RRPA find novel and risky. For large or small-scale commercial applications, the funding of a persistent deterrence campaign may be cost effective; however, such economic evaluations are not always possible or consistent. Our review highlighted areas where field studies may validate the use of deterrent devices mentioned above.

- In a growing population, deterrence at the local scale serves to shift RRPA activity to other stakeholders, be they residential, agricultural, commercial, or natural resources interests. Thus, investment of tax dollars should be directed at research and management actions focused on RRPA population reduction. The greatest potential for population reduction includes shooting as the main tool, but the strategy of a lethal campaign needs to incorporate the behavior of RRPA in response to culling. Efficacy of lethal campaigns will depend not only on biological and economic factors, but also on social license for their use in specific scenarios.

Eradication of RRPA on Kaua'i is unlikely to be successful with the current limits of funding and the large RRPA population. Thus, the goal of limiting RRPA damages over the long-term should be approached through a sustained effort to reduce RRPA numbers along with the use of deterrent devices for short-term relief from damages.

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