Biological Control 101 (2016) 94–102

Contents lists available at ScienceDirect

Biological Control

journal homepage: www.elsevier.com/locate/ybcon

Review

Are avian predators effective biological control agents for rodent pest management in agricultural systems?

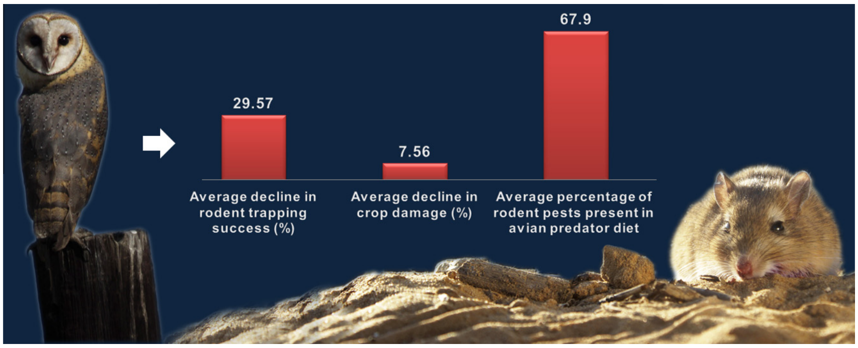
Lushka Labuschagne [a], Lourens H Swanepoel [b,*], Peter J Taylor [b,c,d], Steven R Belmain [e], Mark Keith [a]

[a] Centre for Wildlife Management, University of Pretoria, Pretoria, 0002, South Africa
[b] School of Mathematical & Natural Sciences, Department of Zoology, University of Venda, Thohoyandou, 0950, South Africa
[c] South African Research Chair on Biodiversity Value & Change, University of Venda, Thohoyandou, 0950, South Africa
[d] Core Team Member of the Centre for Invasion Biology, University of Stellenbosch, Stellenbosch, 7602, South Africa
[e] Natural Resources Institute, University of Greenwich, Central Avenue, Chatham Maritime, Kent ME4 4TB, United Kingdom

HIGHLIGHTS

- There is currently insufficient published research on the topic.
- Majority of studies suggests that avian predators seems to have an effect on agricultural rodent pests.
- Clear, quantitative experimental designs and evidence to support above statement is lacking.
- Majority of studies attracted avian predators using nest boxes and/or perches.
- Barn owls were the most frequently assessed avian predator species.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 29 September 2015
Revised 25 June 2016
Accepted 4 July 2016
Available online 5 July 2016

Keywords:
Population dynamics
Tyto alba
Ecologically-based rodent management

ABSTRACT

Worldwide rodent pests are of significant economic and health importance. Controlling rodent pests will, therefore, not only benefit food security but also human and animal health. While rodent pests are most often chemically controlled, there is increased interest in biological control through avian predation. A rich body of research has addressed the impact of avian predators on wild rodent populations, but little is known about the effectiveness of avian predators as biological control agents of rodent pests in agricultural systems. In this study, we systematically reviewed research that investigated different aspects of avian predation on rodent pest populations in order to increase our understanding of the impact and effectiveness of avian predation on rodent pests. Several avian predators (*Tyto alba*, *Elanus axillaris*, *Falco tinnunculus*, *Falco cenchroides*, *Bubo bengalensis*, *Buteo rufinus*) were commonly cited in the biological control of rodents; however, barn owls (*T. alba*) are the most cited species (86% of studies). We found some support that the use of avian predators produced positive, measurable effects where increased presence of avian predators tended to lower rodent pest numbers, resulting in lower crop damage. However, our review highlighted several shortcomings related to research on avian predation of rodent pests. First, research concerning rodent pest control through avian predation was limited (1.86 articles per year). Secondly, we found that studies lack statistical rigor to detect and measure change in rodent pest species abundance. Finally, the majority of studies were short term and therefore not able to evaluate long term sustainable rodent pest population suppression. We suggest that current shortcomings could be adequately addressed with control-treatment studies that quantitatively investigate the effects

---

* Corresponding author at: School of Mathematical and Natural Sciences, Department of Zoology, University of Venda, Private Bag X5050, Thohoyandou, 0950, South Africa.
E-mail address: lourens.swanepoel@univen.ac.za (L.H Swanepoel).

http://dx.doi.org/10.1016/j.biocontrol.2016.07.003

of avian predation on rodent pest populations and agricultural impact. Such research could help develop recommendations regarding the use of avian predators in rodent pest management.

Contents

1. Introduction

Rodents (Mammalia: Rodentia) are among the most important agricultural pests across the globe (Singleton and Petch, 1994; Singleton et al., 2010). This is largely due to their rapid breeding response to favorable environmental conditions, high species diversity and adaptation, widespread geographic distribution and life history characteristics (Leirs, 2003; Singleton et al., 2010). For example, *Mastomys* sp. populations rapidly respond to favorable climatic conditions (e.g. high rainfall) resulting in high densities which can cause significant agricultural damage (Leirs et al., 1997; Odhiambo et al., 2005).

Agricultural damage largely depends on rodent density and the species involved and the damage and impact can be significant during population outbreaks (e.g. 34–100% crop damage; Odhiambo et al., 2005). Furthermore, some rodent species act as reservoirs for various diseases which can influence public health (Taylor et al., 2008; Meerburg et al., 2015; Monadjem et al., 2015). Therefore, controlling rodent pests has the potential to benefit both food security (Makundi and Massawe, 2011), and human health (Munoz-Pedreros et al., 2010).

Rodent management tends to rely on the use of chemical control (e.g. anticoagulant rodenticides and zinc phosphide; Haim et al., 2007; Monadjem et al., 2015). Although the effective application of rodenticides can suppress rodent pest populations, there are some limitations to such an approach. Their misuse can have environmental and management implications (Paz et al., 2013) and can become a health concern to humans and other animals. Direct exposure, secondary poisoning (e.g. predators and scavengers preying/scavenging on dead/dying rodents) or indirect exposure by chemicals leaching into the soil and water causing environmental pollution are possible pathways of concern (Albert et al., 2010; Paz et al., 2013).

Furthermore, rodenticide application can also be prohibitively expensive, especially for resource-poor communities with limited access and a lack of financial means (Makundi and Massawe, 2011). Misuse and incorrect application often only results in temporary population suppression of rodent damage levels (Singleton et al., 1999). Long-term exposure to sub-lethal dosages of rodenticide can and have resulted in physiological and behavioural resistance in rodent populations (Buckle et al., 1994).

The limitations and environmental concerns of chemical rodent pest control have prompted researchers and managers to seek alternative control methods that are both ecologically acceptable and economically viable (Singleton et al., 1999; Makundi and Massawe, 2011; Taylor et al., 2012). Ecologically Based Rodent Management (EBRM) has been proposed as an alternative rodent pest control approach that is both economically and ecologically viable. EBRM is based on increasing our knowledge and understanding of rodent population biology, community ecology, rodent behaviour and natural predation in order to develop sustainable rodent pest management (Singleton et al., 1999; Jacob et al., 2003). Given all other facets, natural predation has been suggested as an attractive, yet under-utilized component in EBRM studies (Makundi and Massawe, 2011).

Attracting predators can have both a direct and indirect effect on prey dynamics (Korpimaki and Krebs, 1996; Carlsen et al., 1999). However, such predation impact depends on prey population cycles, timing of predation, effectiveness of predators and predator characteristics (Salo et al., 2010; Prevedello et al., 2013). The largest effect of increased predation pressure on prey populations occurs when cyclic prey reaches their lowest population sizes (Salo et al., 2010; Prevedello et al., 2013). For non-cyclic populations, the greatest impact of increased predation normally occurs late in the manipulation experiments (Salo et al., 2010). For food supplemented rodents (e.g. rodents impacting on agriculture), increased predation had a large effect to dampen population peaks (Prevedello et al., 2013). As such available evidence indicate that increased predation can affect and to degree limit population size of cyclic and food supplemented rodents (Salo et al., 2010; Prevedello et al., 2013), which are both characteristics of rodent pest impacting agriculture. Including predation in EBRM actions might, therefore, be a valuable strategy to achieve long term rodent pest population suppression.

While the predation impact of mammalian and avian predators on rodent populations have been extensively studied, avian predators appear to be a more attractive group to control rodent pests in agricultural ecosystems. The presence of avian predators creates less human-wildlife conflict than mammalian/reptilian predators (Stein et al., 2010), avian predators seems to be more resilient to extirpation and are able to respond more quickly than mammalian/reptilian predators to prey population fluctuations (Sekercioglu, 2006). The high mobility of avian predators permits a quick response to spatially scattered rodent populations (Andersson and Erlinge, 1977; Sekercioglu, 2006), while in contrast, mammal predators are often sedentary and respond numerically to locally increased pest rodent populations (Andersson and Erlinge, 1977). This suggests that there will be limited ability to quickly attract mammalian predators to areas of high rodent impact. While predation impacts on rodent populations have been intensively studied in natural ecosystems (Salo et al., 2010; Prevedello et al., 2013), research on predation impact on rodent pest populations is limited, especially the effect and impact of avian predation on rodent pests in agriculture (Singleton and Petch, 1994).

In this study, we assessed relevant scientific literature on the use of avian predators as biological agents in rodent pest control, within an agricultural context. We systematically reviewed published studies to determine whether avian predators can successfully reduce rodent pest populations, and, therefore, reduce the damage caused by rodents and increase financial benefit to the agricultural sector. One of the primary aims of the review was to ultimately provide useful information regarding the procedures used in evaluating the actual impact of avian predators as biological control agents, in order to be able to confidently reassure public administrators interested in this control method.

2. Methods

We searched the electronic database Web of Science for published literature relating to the impact of avian predation on rodent pests. We allowed a liberal time period that spanned from 1910 to 2015. Furthermore, we expanded our search to Google Scholar, to include unpublished data/reports as well. We used a combination of the following words and/or phrases: ‘rodents’, ‘avian predators’, ‘rodent pests’, ‘rodent control’, ‘biological rodent control’, ‘predators controlling rodents’.

During the literature search, we followed the PRISMA statement guidelines in recording papers (included and excluded) during each screening stage (Appendix A; Moher et al., 2009). Relevant studies were downloaded and screened using Endnote (©Thomson Reuters), by only selecting papers with the following words in the title and/or in the abstract: ‘avian predators’, ‘rodent control’, ‘biological rodent control’, ‘pest management’. The search was then extended by including papers with appropriate titles within the various reference lists. The full text of all studies that passed the initial screening was then reviewed in detail and we extracted information as presented in Appendix B. We did not include studies conducted on natural rodent populations and only focused on studies reporting on rodent pest populations within agricultural matrices.

In evaluating the potential of avian predators as biological control agents, we used three different measures:

a) We evaluated whether avian predators affected a decline in pest population numbers (either rodent density (rodents/ha) or capture success), especially pre- and post- avian predator increases,
b) We evaluated if the presence of avian predators led to a financial benefit either indirectly due to an increase in crop production decline (by estimating the percentage damage; kg/hectare/year) or directly by evaluating financial benefit (cost/hectare) after avian predators have been introduced, and
c) We evaluated the avian predators’ primary prey to investigate if avian predators remove the main reported rodent pest species.

We further assessed the experimental design of each study, where we classed studies into either non-manipulative (natural monitoring; i.e. studies that did not artificially manipulate avian predator populations), or manipulative (i.e. studies that induced changes in predator and/or prey populations). Manipulative studies, therefore, modified either breeding or perching conditions of avian predators in an effort to increase their abundance.

Where possible we extracted data on a) percentage rodent pests within predator diet, b) rodent trapping success before and after the increase of avian predators, c) percentage crop damage due to rodent pests before and after the increase of avian predators, d) occupancy rate of erected nest boxes. Due to limitations of the data we could not follow traditional meta-analysis approaches to quantity effect sizes (e.g. Hedges’d or ln[R]), we therefore defined effect size as ln (X_e/X_c), where X_e are the mean of the treatment (treatment = increased avian predators) and X_c where the mean of the control (control = normal avian predator density; Salo et al., 2010). Mean values were extracted for rodent trap success and mean crop damage before and after predation effects. Effect size values > 0 indicate that predator increase had a positive effect on the variable measured (e.g. increased rodent trap success), $0 \sim 0$ means no effect and effect size < 0 means that increased predation reduced measured variables (Salo et al., 2010). We used a paired t-test (De Winter, 2013) to test for significance of treatment (i.e. before and after avian predator increase). We also calculated the mean and standard deviation from these studies. Statistical analysis was done in R (R Development Core Team 2011). We report results as mean and standard error, and we used the Shapiro-Wilk test to test for normality (Shapiro and Wilk, 1965).

3. Results

We found that biological control of rodent pests is an active field of research (n = 2086; Appendix A). Even though numerous papers discuss avian predators as biological agents in pest control, few studies have actually been undertaken to investigate the effectiveness and applicability (1.34% of 2086 studies; Appendix C). Other biological rodent control studies included the use of mammalian predators, pathogens, trapping systems, habitat modification and fertility control. We found a fairly stable temporal trend in papers published dealing with avian predators as agricultural pest control (1.08 studies per year), with an increase during 2010 (Appendix D).

3.1. Evaluating avian impact

We found 28 studies where the success of avian predator attraction methods for the purpose of rodent control, have been evaluated. Authors generally monitored three key variables, or combinations thereof, in evaluating the actual impact of avian predation on rodent pests and the associated benefits derived from predation. These include rodent abundance (rodent capture success), crop damage and the frequency of the main rodent pest species in a predator's diet.

3.1.1. Rodent capture success (abundance proxy)

Five studies (18%) determined the effect of avian predators on rodent abundances, while only 11% (n = 3) provided estimates of rodent capture success pre- and post-avian predator increases (Appendix C). Rodent capture success data conformed to normality (W = 0.929, p = 0.596).

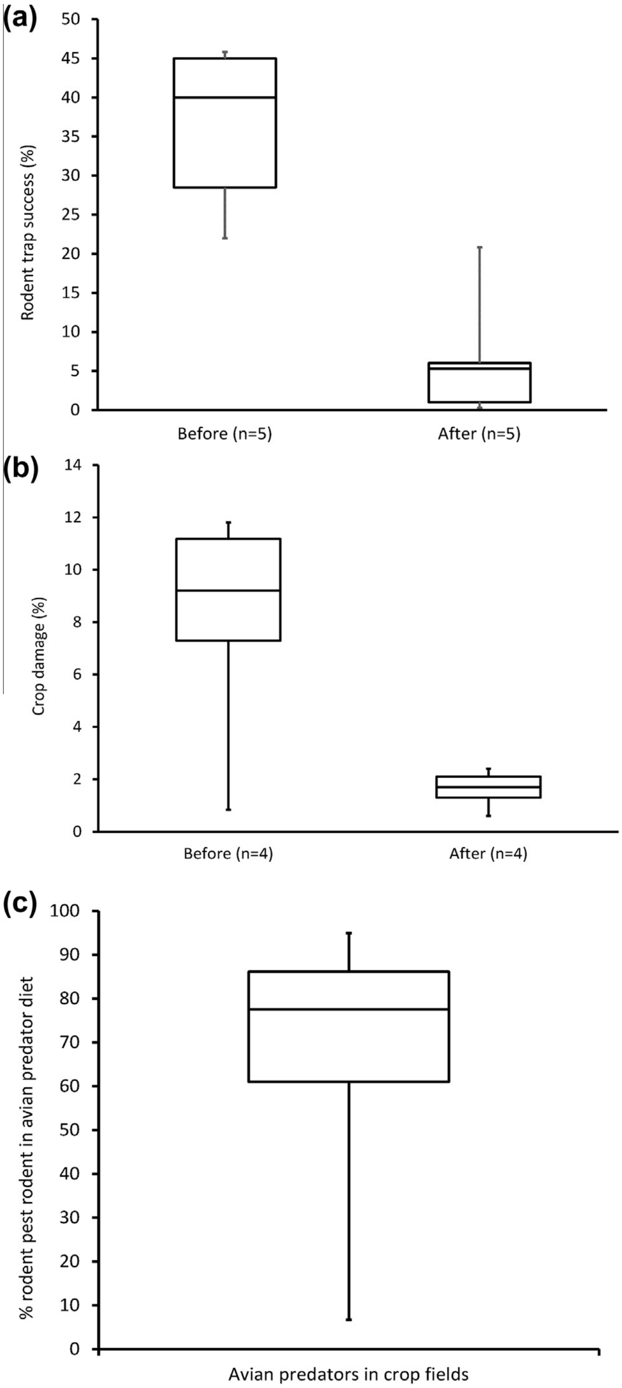


Fig. 1. a) Average percentage rodent pest trapping success, both prior to and post increase of avian predators; b) Average percentage crop damage due to rodents, both prior to and post increase of avian predators; c) Average percentage rodent pests within avian predator diet.

We found that avian predator manipulation had a significant negative affect on pest rodent capture success, with capture success declining 5.4-fold after increased predation (*t*-test, mean $\ln(X_e/X_c) \pm 95\%$ CI = -2.36 ± 0.81, t [4] = 5.57, p = 0.003; Fig. 1a).

3.1.2. Crop damage

Thirty-two percent of studies (n = 9) measured crop damage decline, while only 7% (n = 2) reported on financial benefit due to avian predation (Appendix C). We were able to extract estimations of crop damage from four studies (14%). Crop damage conformed to normality (W = 0.909, p-value = 0.476) and we found that increased avian predation significantly affected crop damage with a 1.2-fold decline in damage (*t*-test, mean $\ln(X_e/X_c) \pm 95\%$ CI = -1.71 ± 0.21, t [3] = 5.60, p = 0.006; Fig. 1b). Increased avian predation seems to be able to maintain crop damage to lower than 5% (Mohd, 1990; Noor et al., 2013), and could lead to financial savings of up to $30/hectare/year (440 kg/hectare/year, 3.24%; Motro, 2011).

3.1.3. Predator diet

The majority of studies (57%; n = 16) investigated avian predator diets, specifically if avian predators were primarily feeding on the rodent pest species. Forty-three percent (n = 12) of studies quantified dietary methods, which were either estimates of number of regurgitated pellets analysed (ranged from 104 to 1676), number of prey items identified (ranged from 162 to 2000), number of rodent carcasses identified (150 rodent carcasses) or number of boxes from which pellets were collected from (38 boxes; Appendix C). One study merely mentioned that predation correlated positively with rodent population fluctuations (Puan, 2010).

Fifty percent of studies (n = 14) provided quantified results in terms of the percentage of rodent pest species contributing to avian predators' diets. Among impacted landscapes rodent pests contributed a large proportion to avian predator diets (mean = 68%; SE = 12.21; Fig. 1c). However, in 7% (n = 2) of studies, rodent pest species were of low importance in avian predator diets, ranging from 6.7 to 11%. In 4% (n = 1) of studies, there was no distinction made between rodent pests and non-rodent pests consumed by avian predators.

Four (14%) of the studies which provided quantified results in terms of the frequency (%) of targeted rodent pest species in avian diet, also determined some sort of measurable effect on either a) rodent abundance or b) crop damage (Appendix C). In one study the main rodent pest species contributed to 80% of the avian predator diet, with a decline of 41.85% in rodent trapping results. In another study, 84.1% of the avian predator diet consisted of the primary rodent pest species, with a decrease of ±40 rodents/0.5 ha in presence of avian predators. A study which focused on crop damage and gross income had a net increase of $220/hectare/harvest, with the target rodent species contributing 64% to avian predator diet. Results of the fourth study indicated a 90% frequency of main rodent pests in avian predator diet and claimed a removal of ±35 000 gerbils annually.

3.1.4. Numerical impact of avian predation

Two studies (7%) attempted to quantify the numerical impact of avian predation on rodent pest populations. Estimates of annual rodent removal ranged from 875 to 2300 rodents per avian predator breeding pair. However, it was not clear from all these studies how rodent removal was estimated, thus drawing conclusions from these results remains difficult.

3.2. Experimental design

The majority of studies (96%; n = 27) followed an experimental design, with manipulation studies being the most common (89%; n = 24), followed by natural monitoring/non-manipulative studies (11%; n = 3).

In manipulative studies, the experimental design involved attracting avian predators. There was variation in how studies manipulated sites to test the effect of avian predators on rodent pest populations (e.g. prior to or during the study; Fig. 2). The majority of manipulation studies (29%; n = 7) erected artificial boxes/perches, and determined pest population dynamics and/or crop damage before and after avian predator abundance increased (Fig. 2).

Of the 24 studies that carried out manipulative techniques, only five studies (21%) mentioned the number of boxes and/or perches erected, although no avian densities prior to or after erection of these structures were indicated. Only 13% (n = 3) estimated avian predator population abundances prior to the erection of nest boxes and/or perches. Fifteen studies (63%) specified either how many boxes became occupied or the number of avian predators that were observed after erection of artificial structures. Avian predator abundances showed great variation in the various studies. Nest box studies were generally successful and had on average an occupancy rate of 58% (95%CI = 48.05%–68.86%).

Non-manipulative studies (i.e. natural monitoring) involved methods where no alterations were made to the study area. These studies included methods such as the collecting and analyzing of regurgitated pellets of avian predators established within a study area. Pellets collected from in and around nesting sites allowed for prey species composition and relative frequency of species within the diet of these birds and provided insight into if avian predators were indeed feeding on and thus removing the primary rodent pest species.

3.3. Avian species used in rodent pest control programmes/studies

Six species of avian predators were commonly reported on in review studies (Fig. 3), with barn owls (*Tyto alba*) being the most frequent avian predator (86%; Fig 3), followed by common kestrels

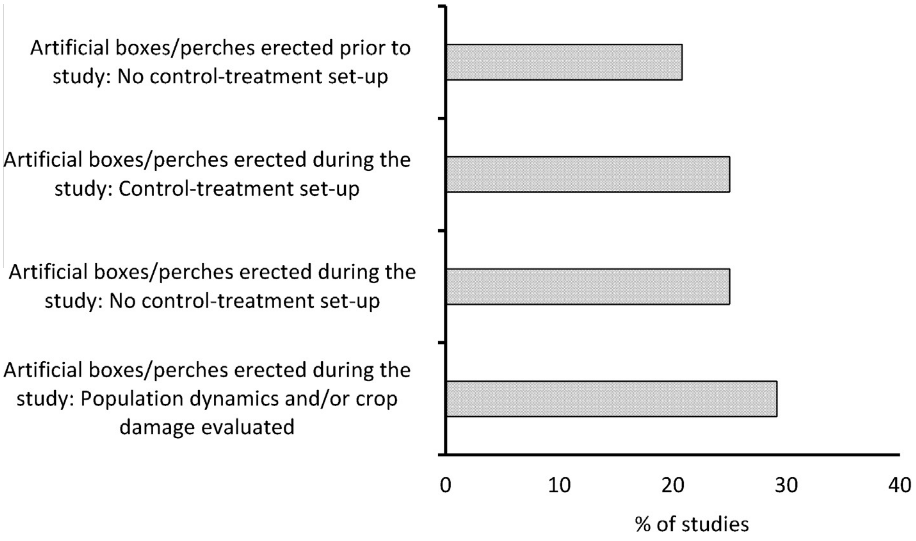


Fig. 2. Representative percentages for various manipulative techniques used in the 24 bio-control studies that indicated manipulative techniques.

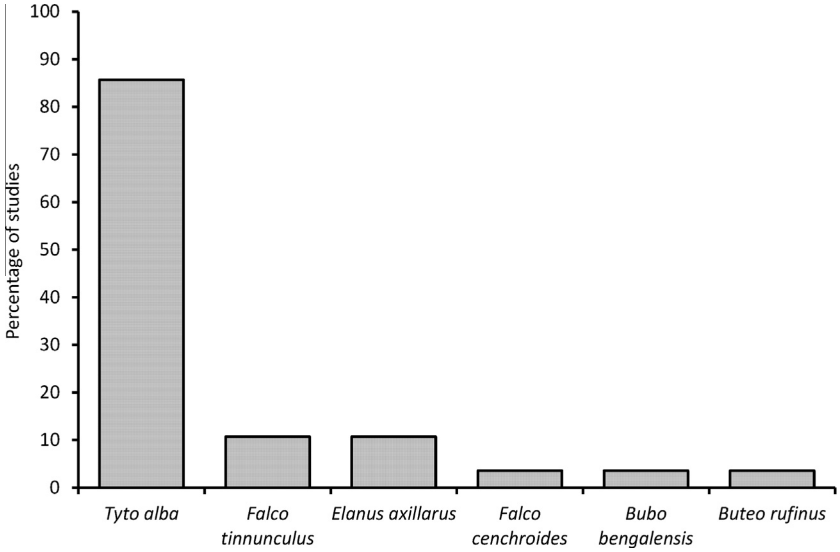


Fig. 3. Representative percentages for avian predator species used in 28 selected bio-control studies.

Table 1
Representative percentages of agricultural rodent pests assessed in the 26 studies that indicated pest species, as well as the avian predator and crop/vegetation system assessed within the same study.

Rodent species	% of studies	Avian predator(s) in study	Crop/vegetation type affected
Bandicota bengalensis	3.85	*Bubo bengalensis*	Wheat, maize, sorghum, millet, rice, lentils, leafy vegetables, figs, pomegranate, apple, quava
Bandicota indica	3.85	*Bubo bengalensis*	Wheat, maize, sorghum, millet, rice, lentils, leafy vegetables, figs, pomegranate, apple, quava
Gerbilliscus afra	7.69	*Tyto alba*	Wheat
Gerbilliscus indica	3.85	*Bubo bengalensis*	Wheat, maize, sorghum, millet, rice, lentils, leafy vegetables, figs, pomegranate, apple, quava
Gerbilliscus sp.	3.85	*Falco tinnunculus, Buteo rufinus*	Not specified
Mastomys natalensis	7.69	*Tyto alba*	Maize
Microtus arvalis	3.85	*Tyto alba, Falco tinnunculus*	Not specified
Microtus californicus	3.85	*Tyto alba*	Vineyards
Microtus socialus	3.85	*Tyto alba*	Wheat, alfalfa
Microtus guentheri	3.85	*Tyto alba*	Alfalfa
Mus booduga	3.85	*Bubo bengalensis*	Wheat, maize, sorghum, millet, rice, lentils, leafy vegetables, figs, pomegranate, apple, quava
Mus domesticus	3.85	*Elanus axillaris, Falco cenchroides*	Soybean
Mus musculus	3.85	*Bubo bengalensis*	Wheat, maize, sorghum, millet, rice, lentils, leafy vegetables, figs, pomegranate, apple, quava
Mus saxicola	3.85	*Bubo bengalensis*	Wheat, maize, sorghum, millet, rice, lentils, leafy vegetables, figs, pomegranate, apple, quava
Necromys lasiurus	3.85	*Tyto alba*	No vegetation, carrier of Hantavirus
Octodon bridgesi	3.85	*Tyto alba*	Pine
Oligoryzomys longicaudatus	3.85	*Tyto alba*	No vegetation, carrier of Hantavirus
Rattus argentiventer	15.38	*Tyto alba*	Rice fields, sugar cane
Rattus rattus	3.85	*Bubo bengalensis*	Wheat, maize, sorghum, millet, rice, lentils, leafy vegetables, figs, pomegranate, apple, quava
Rattus sp.	15.38	*Tyto alba, Elanus axilliaris*	Oil palms
Rattus rattus diardii	3.85	*Tyto alba*	Oil palms
Rattus rattus mindanensis	3.85	*Tyto alba*	Rice fields
Rattus tiomanicus	3.85	*Tyto alba*	Cocoa
Sigmodon	3.85	*Tyto alba*	Sugar cane
Thomomys bottae	7.69	*Tyto alba*	Vineyards

(*Falco tinnunculus*; 11%; Fig. 3) and black-shouldered kites (*Elanus axillaris*; 11%; Fig. 3).

3.4. Rodent pest species and cropping systems

Our review highlighted a total of 25 rodent species as potential pest species (Table 1). However, rodent pests were dominated by the genus *Rattus* sp. (43% of studies; n = 12), followed by *Gerbilliscus* sp. (14% of studies; n = 4). Rodent pests from 4 studies (14%) were alien-invasive and rodents from 15 studies (54%) were native-invasive of nature.

Furthermore, 86% of the studies indicated the type of crop/vegetation type that was damaged by rodent pests. The most frequently indicated crop/vegetation types were oil palms (*Elaeis guineensis*) and rice fields (*Oryza* sp.; 20% each), followed by wheat (*Triticum* sp.), maize (*Zea mays*) and alfalfa (*Medicago sativa*; 12% each; Table 1).

3.5. Geographical locations and duration of studies

While we found studies from a global sample (Appendix E), the majority of the studies were undertaken in Malaysia (36%; n = 10). The average duration of studies were 29 months (95%CI = 17.59–40.41), with the longest running study being 10 years (Appendix C).

4. Discussion

4.1. Number of articles

Finding long term sustainable solutions to rodent pests in agricultural systems remains elusive (Vibe-Peterson, 2003; Makundi and Massawe, 2011). Especially among resource poor farmers, rodent pests remain a key factor affecting food production (Makundi and Massawe, 2011). While progress has been made in EBRM, incorporating predation in EBRM strategies appears to be limited. Our review has highlighted the paucity of research related to predation, especially quantitative research incorporating predation into EBRM. There are several factors that can explain this lack of research, not necessarily mutually exclusive.

First, the population dynamics of both avian predators and rodent pests needs to be taken into account (Wood and Fee, 2003; Ostfeld and Holt, 2004; Makundi and Massawe, 2011). Since rodent species possess a rather complex biology and behaviour (Leirs, 2003) and a great deal of avian predators exhibit elusive behaviour and occur in relative low densities (Ibarra et al., 2014), monitoring and obtaining results can be rather difficult. Secondly, there can be both a temporal and spatial segregation between rodent pests and avian predators, which makes it difficult finding an experimental study system (Andersson and Erlinge, 1977). Thirdly, one needs a viable avian population to study, which is not necessarily available in a natural setting (Devane et al., 2004; Kan et al., 2013). It requires effort, time and labour to increase avian predator densities, where this process generally involves erecting artificial nest boxes (Wood and Fee, 2003). Lastly, as seen in several papers included in this review (e.g. Mohamad and Goh, 1991; Hafidzi et al., 1999; Motro, 2011), such studies requires a long-term approach where it may take an extensive period for avian predators to occupy boxes, reach an appropriate density and potentially exhibit an impact.

4.2. Impact of avian predators and experimental design

Overall our analysis suggests that attracting avian predators can produce measureable effects on rodent pests, and in some cases can elicit declines in pest capture success and associated crop damage. Our results concur with several other meta-analyses (e.g. Salo et al., 2010; Prevedello et al., 2013) lending support that attracting avian predators can be useful in the biological control of rodent pests (Paz et al., 2013). However, the majority of studies lacked replicated experimental treatment setups to detect causation which is needed to conclusively attribute declines in rodent abundance and crop damage to increased avian predator abundance. This result concurs with example Singleton and Petch (1994), Wood and Fee (2003) and Sekercioglu (2006) who have questioned the effectiveness of avian predators as biological control agents.

Observational studies, determining only if avian predator diet comprises mainly the primary pest species, provide little evidence that these avian predators are effective in controlling rodent pests (Moore et al., 1998). Without investigating the relationship between avian predator density, prey consumption rate, rodent pest density and associated agricultural crop losses it would be difficult to make assertive conclusions as to the actual impact of avian predators on rodent populations.

Furthermore, knowing that predators reduce prey population numbers is not adequate (Ostfeld and Holt, 2004). The strength of predator effects needs to be compared to other factors influencing rodent numbers. If food is the primary regulator of rodent numbers, then any predation impact may be overshadowed by bottom-up processes, resulting in only trivial effects on rodent numbers (Ostfeld and Holt, 2004). It is thus necessary to conjoin other ecological factors, such as food supply, to determine the actual impact of predators.

The majority of studies made use of manipulative experimental designs, which comprised manipulating avian predator densities (e.g. by attracting avian predators by the erection of artificial nest boxes and/or perches; Paz et al., 2013). Such an experimental design could be used to untangle effects of predation and natural mortality on rodent populations (Krebs, 1999). In general, manipulative experiments should have a control unit, typically defined as an experimental unit which has received no treatment (e.g. no avian attraction methods). Without a control unit, it is impossible to conclude anything definite about the experiment. Before and after comparisons can also serve as acceptable methods of assessment and can be statistically powerful (Krebs, 1999).

Studies were generally of short duration and lacked replicates to detect population changes and can thus only be seen as speculative (Hafidzi and Mohd, 2003), owing to considerable year to year variation in communities and ecosystems (Krebs, 1999). For example, the numeric response by rodent pest species may exceed those of the predator (Singleton and Petch, 1994), which may only be noticed when studies are continuous. It is also crucial to determine avian predator population sizes prior to erection of nest boxes as well as to continue monitoring after the initial occupancy of nest boxes. This is due to the fact that avian predators may aggregate or disperse when prey species are unable to maintain their densities, e.g. near the end of the non-breeding season (Singleton and Petch, 1994). Continued and long term investigation is thus needed to determine stable predator populations, pest population sizes and losses (Wood and Fee, 2003).

Rodent pest population dynamics were also limited to indexes (capture success), which have been shown to have limited statistical power in population ecology (Pankakoski, 1979; Whisson et al., 2005). However, preliminary results may be important since can they inform and encourage farmers to consider alternative, more environmentally-friendly pest management techniques (Motro, 2011).

4.3. Why barn owls are so frequently considered as biological rodent control agents

Although research on other avian predators are cited, barn owls are currently particularly attractive avian predators for controlling pest species. The barn owl is one of the most widespread avian predators in the world (Jaksic et al., 1982; Meyrom et al., 2009; Kan et al., 2013), where they are easily attracted and extremely versatile in selecting nesting sites (Colvin, 1985; Lee, 1997). Even though their hunting ranges might differ in size depending on season and prey availability, these owls are not migratory species, occupying and hunting in one specific area all year round (Glue, 1970; Bond et al., 2004). Furthermore, barn owls' home ranges, which have been recorded up to 5 km^2, are known to overlap, where they may display minor territorial behaviour only during the breeding season (Hafidzi et al., 2003; Smith et al., 2014).

Unlike many other predatory birds, barn owl breeding rates typically respond to food abundance (Taylor, 1994). Another attractive attribute is the fact that small mammals, especially rodents, are the main prey source of barn owls and its diet is an accurate reflection of the local fauna composition as well as population fluctuations of prey (Alvarez-Castaneda et al., 2004; Tores et al., 2005; Granjon and Traore, 2007; Magrini and Facure, 2008; Charter et al., 2009). Despite barn owls' relatively smaller size, their high metabolic rate enables them to exhibit a relatively high consumption rate and are reported to feed up to one fourth of their body weight in prey daily (Marti et al., 2005).

4.4. Rodent pest species

The majority of rodent pest species mentioned in selected studies were invasive of nature. Habitat characteristics are important determinants of rodent species diversity; in more homogeneous habitats, the diversity of rodents is usually low, although certain species tend to be abundant because of higher resource availability (Taylor et al., 2012).

In contrast, habitat heterogeneity allows more species to coexist because of availability of more niches. On occasion, agriculture has been blamed for cultivating its own pests (Evenden, 1995). Agricultural expansion may result in conservation threats to native small mammals from habitat alteration, introduction of niches better suited to introduced pest species, negative impacts of introduced species and negative consequences of rodent-control measures such as indiscriminate rodenticide use.

A better understanding of small-mammal community dynamics and habitat-use patterns in agro-ecosystems is critical to finding a balance between the often conflicting imperatives of conservation and pest management. EBRM addresses the need for a balanced approach that enhances both nature conservation, crop production and protection (Makundi and Massawe, 2011; Taylor et al., 2012).

4.5. Geographical location

We found that research on avian predators acting as rodent pest control is quite widespread globally. However, little of this research has been done in developing countries. Such developing countries are especially in need of alternative rodent management techniques due to the majority of farmers being resource poor and not being able to afford rodenticides (Singleton et al., 1999). Threats from rodent pests are also far more severe in these countries, as their damage in agricultural fields and crop storage may directly affect the human population who are much more dependent on their crops, due to limited alternative food sources (Vibe-Peterson, 2003).

Unfortunately, many cultures in developing countries, believe that the sight or sound of certain avian predators, such as owls, results in misfortune and/or death (Ogada and Kibuthu, 2008). For example in Malawi, community members (92%) commonly believe that owls bring bad luck, foretell death and are associated with witchcraft, which often results in owl persecution (Mikolla and Mikolla, 1997). Owls are also commonly killed for being noisy, use in traditional medicine, for fun, and for food (Mikolla and Mikolla, 1997). These cultural views and attitudes thus often place a significant limit on the use of owls in small holder farming communities. Furthermore, fewer resources are allocated for these kinds of studies or control programmes by governments in developing countries and donor organizations, than those allocated to funding of contemporary issues such as malaria and HIV (Makundi and Massawe, 2011).

5. Conclusion

Our review highlighted several key issues related to avian predators in biological control of rodent pests. First, the number of studies was limited, suggesting that a stimulus in research concerning avian predation on agricultural rodent pests is needed. Secondly, the majority of studies lacked experimental designs (multiple time series design, control, replication) to allow for informative analysis. Thirdly the majority of studies relied on simple indexes to quantify rodent and avian predator abundance. We suggest that studies investigating the use of avian predation as a biological control agent in rodent pests should benefit from the following suggestions and guidelines:

- Researchers should employ a ‘meta-analytic’ thinking framework (see Nakagawa and Cuthill, 2007) when setting up experimental control and treatment studies. Such a framework will allow for calculating and reporting effect size statistics and key information pieces needed for future meta-analysis (e.g. Standard deviation, sample size; Nakagawa and Cuthill, 2007).
- Studies using manipulative experimental designs (e.g. attracting avian predators by the erection of artificial nest boxes and/or perches) are generally better suited to unravel the effect of predation and other environmental/ecological aspects on rodent pests.
- Studies reviewed here in general did not related rodent abundance to crop damage (Brown et al., 2007). We suggest that researchers should attempt to extent this relationship to include avian predator densities as well. Therefore, researchers should estimate avian density and relate these to rodent abundance and ultimately to crop damages. Such results will enable managers to modify or manage landscapes at appropriate levels to increase avian predator densities to effective densities. A further useful approach would be to use food webs to relate rodent abundance to predator densities within these agricultural matrixes (Memmott, 2009).
- Reviewed studies generally used density proxies (e.g. trapping success), we suggest that such indices are not useful since they do not take into account variation in detection or capture probabilities during capture (Anderson, 2001). We suggest that researchers should rather employ robust statistical techniques (e.g. mark recapture; Hayward et al., 2015).
- Finally, quantifying the impact and use of predation in EBRM will require long term studies (Krebs, 2015). We suggest that funding agencies and researchers attempting to investigate these issues should invest in long term studies (several avian predator and rodent generations). Furthermore, it would be fruitful to investigate the long term effect of predation on the survival rates or rodent pests, rather than densities or proxies like capture success. Again, such an approach should have control sites and rodent presence/survival should be related to crop damage.

We believe that following these suggestions will greatly improve our understanding of the impact of avian predations on rodent pests. Nonetheless, we highlight that several studies reported measurable impacts following increases in avian predator densities, suggesting avian predators can be key components in EBRM strategies.

Acknowledgments

This work was funded partly from an EU 9th European Development Fund grant from the African Caribbean and Pacific Science and Technology Programme (FED-2013-330-223), SASOL Agricultural Trust and National Research Foundation (LHS #88179). The contents of this document are the sole responsibility of the authors and can under no circumstances be regarded as reflecting the position of the European Union, SASOL or NRF. We thank the anonyms reviewers for the comments that improved the manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocontrol.2016.07.003.

References

Alvarez-Castaneda, S.T., Cardenas, N., Mendez, L., 2004. Analysis of mammal remains from owl pellets (*Tyto alba*), in a suburban area in Baja California. J. Arid Environ. 59, 59–69.

Albert, C.A., Wilson, L.K., Mineau, P., Trudeau, S., Elliott, J.E., 2010. Anticoagulant rodenticides in three owl species from Western Canada, 1988–2003. Arch. Environ. Contam. Toxicol. 58, 451–459.

Andersson, M., Erlinge, S., 1977. Influence of predation on rodent populations. Oikos 29, 591–597.

Anderson, D.R., 2001. The need to get the basics right in wildlife field studies. Wildlife Soc. B 29, 1294–1297.

Bond, G., Burnside, N.G., Metcalfe, D.J., Scott, D.M., Blamire, J., 2004. The effects of land-use and landscape structure on barn owl (*Tyto alba*) breeding success in southern England, U.K. Landscape Ecol. 20, 555–566.

Brown, P.R., Huth, N.I., Banks, P.B., Singleton, G.R., 2007. Relationship between abundance of rodents and damage to agricultural crops. Agric. Ecosyst. Environ. 120, 405–415.

Buckle, A.P., Prescott, C.V., Ward, K.J., 1994. Resistance to the first and second generation anticoagulant rodenticides – a new perspective. In: Proceedings of the Sixteenth Vertebrate Pest Conference. University of Nebraska, Lincoln.

Carlsen, M., Lodal, J., Leirs, H., Jensen, T.S., 1999. The effect of predation risk on body weight in the field vole, *Microtus agrestis*. Oikos 87, 277–285.

Charter, M., Izhaki, I., Meyrom, K., Motro, Y., Leshem, Y., 2009. Diets of barn owls differ in the same agricultural region. Wilson J. Ornithol. 121, 378–383.

Colvin, B.A., 1985. Common barn owl population decline in Ohio and the relationship to agricultural trends. J. Field Ornithol. 56, 224–235.

Devane, D., Begley, C.M., Clarke, M., 2004. How many do I need? Basic principles of sample size estimation. J. Adv. Nurs. 47, 297–302.

De Winter, J.C.F., 2013. Using the student’s *t*-test with extremely small sample sizes. Pract. Assess., Res. Eval. 18, 1–12.

Evenden, M.D., 1995. The laborers of nature: economic ornithology and the role of birds as agents of biological pest control in North American agriculture, Ca., 1880–1930. For. Conserv. Hist. 39, 172–183.

Glue, D.E., 1970. Avian predator pellet analysis and the mammologist. Mamm. Rev. 1, 53–62.

Granjon, L., Traore, M., 2007. Prey selection by barn owls in relation to small-mammal community and population structure in a Sahelian agro-ecosystem. J. Trop. Ecol. 23, 199–208.

Hafidzi, M.N., Hamzah, M.L., Jamaluddin, M.S., 2003. Ranging behaviour of *Tyto alba* in rice field from radio telemetry studies. Malays. Appl. Biol. 32, 47–51.

Hafidzi, M.N., Kamarudin, A.A., Zulkifli, A., 1999. Barn owls as a biological control agent of rats in paddy fields. Towards efficient biodiversity and bioresources management for effective biological control. In: Proc. Symposium on Biological Control in the Tropics, Serdang, Malaysia. MARDI Training Centre, Kuala Lumpur, pp. 85–88.

Hafidzi, M.N., Mohd, N., 2003. The use of the barn owl, Tyto alba, to suppress rat damage in rice fields in Malaysia. In: Singleton, G., Hinds, L.A., Krebs, C.J., Spratt, D.M. (Eds.), Rats, Mice and People: Rodent Biology and Management, ACIAR

Monograph No. 96. Australian Centre for International Agricultural Research, Canberra, pp. 274–276.

Haim, A., Shanas, U., Brandes, O., Gilboa, A., 2007. Suggesting the use of integrated methods for vole population management in alfalfa fields. Integr. Zool. 2, 184–190.

Hayward, M.W., Boitani, L., Burrows, N.D., Funston, P.J., Karanth, K.U., MacKenzie, D.I., Pollock, K.H., Yarnell, R.W., 2015. Ecologists need robust survey designs, sampling and analytical methods. J. Appl. Ecol. 52, 286–290.

Ibarra, J.T., Martin, K., Altamirano, T.A., Bonacic, C., 2014. Factors associated with the detectability of owls in South American temperate forests: Implications for nocturnal raptor monitoring. J. Wildlife Manage. 78, 1078–1086.

Jacob, J., Sudarmaji, Singleton, G.R., 2003. Ecologically based management of rice-field rats on a village scale in West Java: experimental approach and assessment of habitat use. In: Singleton, G., Hinds, L.A., Krebs, C.J., Spratt, D.M. (Eds.), Rats, Mice and People: Rodent Biology and Management, ACIAR Monograph No. 96. Australian Centre for International Agricultural Research, Canberra, pp. 191–196.

Jaksic, F.M., Seib, R.L., Herrera, C.M., 1982. Predation by the barn owl (*Tyto alba*) in Mediterranean habitats of Chile, Spain and California: a comparative approach. Am. Midl. Nat. 107, 151–162.

Kan, I., Motro, Y., Horvitz, N., Kimhi, A., Leshem, Y., Yom-Tov, Y, Nathan, R., 2013. Agricultural rodent control using Barn Owls: is it profitable? Am. J. Agric. Econ., 1–20

Korpimaki, E., Krebs, C.J., 1996. Predation and population cycles of small mammals. Bioscience 46, 754–764.

Krebs, C.J., 2015. One hundred years of population ecology: successes, failures and the road ahead. Integr. Zool. 10, 233–240.

Krebs, C.J., 1999. Ecological Methodology, 2nd ed. Addison-Wesley Educational Publishers Inc., USA.

Lee, C.H., 1997. Barn owl for field rat control in cocoa. J. Trop. Agric. Food Sci. 25, 43–54.

Leirs, H., 2003. Management of rodents in crops: the pied piper and his orchestra. In: Singleton, G., Hinds, L.A., Krebs, C.J., Spratt, D.M. (Eds.), Rats, Mice and People: Rodent Biology and Management, ACIAR Monograph No. 96. Australian Centre for International Agricultural Research, Canberra, pp. 180–190.

Leirs, H., Stenseth, N.C., Nichols, J.D., Hines, J.E., Verhagen, R., Verheyen, W., 1997. Stochastic seasonality and nonlinear density-dependent factors regulate population size in an African rodent. Nature 389, 176–180.

Magrini, L., Facure, K.G., 2008. Barn owl (*Tyto alba*) predation on small mammals and its role in the control of hantavirus natural reservoirs in periurban area in southeastern Brazil. Braz. J. Biol. 68, 733–740.

Makundi, R.H., Massawe, A.W., 2011. Ecologically based rodent management in Africa: potential and challenges. Wildlife Res. 3, 588–595.

Marti, C.D., Poole, A.F., Bevier, L.R., 2005. Barn Owl (*Tyto alba*), The birds of North America online. In: Poole, A. (Ed.). Cornell Lab of Ornithology.

Meerburg, B.G., Singleton, G.R., Kiljstra, A., 2015. Rodent-borne diseases and their risks for public health. Crit. Rev. Microbiol. 35, 221–270.

Memmott, J., 2009. Food webs: a ladder for picking strawberries or a practical tool for practical problems? Philos. Trans. R. Soc., B 364, 1693–1699.

Meyrom, K., Motro, Y., Leshem, Y., Aviel, S., Izhaki, I., Argyle, F., Charter, M., 2009. Nest-box use by the barn owl *Tyto alba* in a biological pest control programme in the Beit She'an valley, Israel. Ardea 97, 463–467.

Mikolla, H., Mikolla, H., 1997. General public owl knowledge in Malawi. Soc. Malawi J. 50, 13–35.

Mohamad, S., Goh, N.S., 1991. The use of barn owl (*Tyto alba*) to control ricefield rats – an experience in Seberang Perak. MAPPS Newslett. 15, 20.

Mohd, S., 1990. Barn owls (*Tyto alba*) for controlling rice field rats. MAPPS Newslett. 14, 51.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Ann. Intern. Med. 151, 264–269.

Monadjem, A., Taylor, P.J., Denys, C., Cotterill, F.P.D., 2015. Rodents of Sub-Saharan Africa: A Biogeographic and Taxonomic Synthesis. De Gruyter Publishers, Berlin, Germany.

Moore, T., Van Vuren, D., Ingels, C., 1998. Are barn owls a biological control for gophers? Evaluating effectiveness in vineyards and orchards. In: Baker, R.O., Crabb, A.C. (Eds.), Proceedings 18th Vertebrate Pest Conference. Published at University of California, Davis, pp. 394–396.

Motro, Y., 2011. Economic evaluation of biological rodent control using barn owls *Tyto alba* in alfalfa. In: Jacob, J., Esther, A. (Eds.), 8th European Vertebrate Pest Management Conference: Book of Abstracts. Arno Brynda GmbH, Berlin, Germany, pp. 79–80.

Munoz-Pedreros, A., Gil, C., Yanez, J., Rau, J.R., 2010. Raptor habitat management and its implication on the biological control of the hantavirus. Eur. J. Wildlife Res. 56, 703–715.

Nakagawa, S., Cuthill, I.C., 2007. Effect size, confidence interval and statistical significance: a practical guide for biologists. Biol. Rev. 82, 591–605.

Noor, H.H., Cik, M.R., Suhaidi, H., 2013. Control measures and integrated approach for major pests of oil palm in Felda. MPOB Palm Oil Congress (PIPOC), KLCC Kuala Lumpur.

Odhiambo, R., Makundi, R., Leirs, H., Verhagen, R., 2005. Community structure and seasonal abundance of rodents of maize farms in Southwestern Tanzania. Belgium J. Zool. 135, 113–118.

Ogada, D.L., Kibuthu, P.M., 2008. Conserving Mackinder's eagle owls in farmlands of Kenya: assessing the influence of pesticide use, tourism and local knowledge of owl habits in protecting a culturally loathed species. Environ. Conserv. 35, 252–260.

Ostfeld, R.S., Holt, R.D., 2004. Are predators good for your health? Evaluating evidence for top-down regulation of zoonotic disease reservoirs. Front. Ecol. Environ. 2, 13–20.

Pankakoski, E., 1979. The cone trap – a useful tool for index trapping of small mammals. Ann. Zool. Fenn. 16, 144–150.

Paz, A., Jareno, D., Arroyo, L., Javier, V., Arroyo, B., Mougeot, F., Luque-Larena, J.J., Fargallo, J.A., 2013. Avian predators as biological control system of common vole (*Microtus arvalis*) populations in north-western Spain: experimental set-up and preliminary results. Pest Manag. Sci. 69, 444–450.

Prevedello, J.A., Dickman, C.R., Vieira, M.V., Vieira, E.M., 2013. Population responses of small mammals to food supply and predators: a global meta-analysis. J. Anim. Ecol. 82, 927–936.

Puan, C.L., 2010. Interactions among Rodents, Owls, Food Resources and Habitat Structure in a Malaysian Oil Palm Agroecosystem (Ph.D. thesis). The University of Queensland, Australia.

Salo, P., Banks, P.B., Dickman, C.R., Korpimäki, E., 2010. Predator manipulation experiments: impacts on populations of terrestrial vertebrate prey. Ecol. Monogr. 80, 531–546.

Sekercioglu, C.H., 2006. Increasing awareness of avian ecological function. Trends Ecol. Evol. 21 (8).

Shapiro, S.S., Wilk, M.B., 1965. An analysis of variance test for normality (complete samples). Biometrika 52, 591–611.

Singleton, G., Belmain, S., Brown, P., Hardy, B., 2010. Rodent Outbreaks: Ecology and Impacts. International Rice Research Institute, Manila, Philippines.

Singleton, G.R., Leirs, H., Hinds, L.A., Zhang, Z., 1999. Ecologically-based management of rodent rests – re-evaluating our approach to an old Problem. In: Singleton, G.R., Hinds, L.A., Leirs, H., Zhang, Z. (Eds.), Ecologically-Based Management of Rodent Pests. Brown Prior Anderson, Melbourne, Australia, pp. 17–29.

Singleton, G.R., Petch, D.A., 1994. A Review of the Biology and Management of Rodent Pests in Southeast Asia. K&B Publications, Canberra, Australia.

Smith, D.G., Wilson, C.R., Frost, H.H., 2014. History and ecology of a colony of barn owls in Utah. The Condor 76, 131–136.

Stein, A.B., Fuller, T.K., Damery, D.T., Sievert, L., Marker, L.L., 2010. Farm management and economic analyses of leopard conservation in north-central Namibia. Anim. Conserv. 13, 419–427.

Taylor, I., 1994. Barn Owls: Predator–Prey Relationships and Conservation. Cambridge University Press, Great Britain.

Taylor, P.J., Arntzen, L., Hayter, M., Iles, M., Frean, J., Belmain, S.R., 2008. Understanding and managing sanitary risks due to rodent zoonoses in an African city: beyond the Boston Model. Integr. Zool. 3, 38–50.

Taylor, P.J., Downs, S., Monadjem, A., Eiseb, S.J., Mulungu, L.S., Massawe, A.W., Mahlaba, T.A., Kirsten, F., Von Maltitz, E., Malebane, P., Makundi, R.H., Lamb, J., Belmain, S.R., 2012. Experimental treatment-control studies of ecologically based rodent management in Africa: balancing conservation and pest management. Wildlife Res. 39, 51–61.

Tores, M., Motro, Y., Yom-Tov, Y., 2005. The barn owl – a selective opportunist predator. Israel J. Zool. 51, 349–360.

Vibe-Peterson, S., 2003. Predation Pressure and Population Dynamics of African Mastomys Mice – Possibilities for Integrated Pest Management? (PhD. thesis). The Royal Veterinary & Agricultural University, Denmark.

Whisson, D.A., Engeman, R.M., Collins, K., 2005. Developing relative abundance techniques (RATs) for monitoring rodent populations. Wildlife Res. 32, 239–242.

Wood, B.J., Fee, C.G., 2003. A critical review of the development of rat control in Malaysian agriculture since the 1960s. Crop Protect. 22, 445–461.