Population Viability Analysis to Inform Conservation Planning for the Philippine Eagle (*Pithecophaga jefferyi*)

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Executive Summary

The Philippine Eagle, one of the rarest birds of prey globally and the Philippines' national bird, is listed as Critically Endangered by the IUCN due to habitat loss, hunting, and other anthropogenic threats. This report summarises findings from a 2024 Population Viability Analysis (PVA) and threat assessment workshop led by the IUCN SSC Conservation Planning Specialist Group in collaboration with the Philippine Eagle Foundation and the Department of Environment and Natural Resources, - Biodiversity Management Bureau.

Three main populations remain (Luzon, Mindanao, Eastern Visayas), with Leyte considered extirpated. Across all regions, habitat loss and degradation are the most pressing threats, followed by direct mortality, disturbance, prey depletion, and disease. Logging, mining, land conversion, and accidental trapping are widespread concerns, particularly in Luzon and Mindanao. The report provides an updated, systematic and detailed characterisation of threats' distribution, perceived severity and the mechanisms by which they affect populations.

A PVA model was developed to identify demographic drivers of population stability and test the impacts of key threats. Due to the limited availability of empirical data, a series of theoretical modelling scenarios were created to investigate and test different aspects of the species' demography. A multifactorial approach to sensitivity testing was used to evaluate the relative importance of demographic parameters and infer the effect of specific threats. Sub-adult mortality emerged as the most influential factor affecting the long-term viability of populations. Sub-adult mortality accounted for over 90% of the variation in population growth projections. Even modest increases led to the most marked changes in population simulations.

Breeding senescence (early reproductive cessation) was also found to dramatically impact gene diversity and adult breeding population size. Extending reproductive age increased growth rates and population size. This highlights the urgency of collecting more empirical data on this parameter.

Habitat availability and initial population size also contribute to long-term viability, and are likely to be linked to the effects of sub-adult mortality, e.g. sub-adults put themselves in harm's way as they disperse into anthropic habitats due to the lack of suitable habitat.

Recommendations

To ensure the long-term survival of the Philippine Eagle, conservation efforts must begin with a focused effort to reduce sub-adult mortality. This age group appears to be particularly vulnerable, likely due to their tendency to range widely in search of territories, putting them at greater risk of threats such as hunting, trapping, and habitat disturbance.

Alongside this, there is an urgent need to improve the availability and accuracy of demographic data. Currently, many key parameters such as survival rates, population trends, and dispersal behaviour remain poorly understood. Establishing a systematic, long-term monitoring program would help fill these knowledge gaps and enable more precise modelling and management.

Another critical area for further investigation is the reproductive lifespan of the species. Observations from captivity suggest that Philippine Eagles may stop breeding at around 25 years of age. However,

it remains unclear whether this is also true in the wild. Understanding whether eagles can continue breeding later into life could significantly influence future conservation strategies, particularly those aimed at maintaining a robust breeding population.

Habitat protection must also remain a central pillar of conservation planning. Increasing the number of secure, well-managed territories for the species will not only support a larger breeding population but also reduce competition and conflict that may arise when eagles are forced into marginal or fragmented habitats.

Introduction

The Philippine Eagle (*Pithecophaga jefferyi*) is a rare monotypic bird of prey (Accipitriformes, Accipitridae) endemic to the Philippines. The species is a source of national pride and was proclaimed the Philippines' national bird through a presidential proclamation in 1995 (No. 615 s. 1995). The Philippine Eagle is currently listed as Critically Endangered under criterion A2cd (a population reduction estimated or inferred based on a decline in area of occupancy (AOO), the extent of occurrence, (EOO), habitat quality, as well as concerning levels of exploitation), and C2a(ii) (an observed, estimated or projected continuing decline AND a 90-100% decline of mature individuals in at least one of the subpopulations. The species has been classified as CR since 1994 (Clark et al., 2015). Forest destruction and fragmentation are thought to be the principal long-term threats. Mining applications pose an additional threat. Bycatch and direct persecution are likely to be impactful in the short term (Miranda et al., 2008), with many birds being rescued and rehabilitated from trapping and gunshot wounds.

There currently are three remaining populations in the islands of Luzon, Mindanao and Samar, in the Eastern Visayas (Sutton et al., 2023). The species has been extirpated from Leyte (Eastern Visayas), probably due to the effects of Typhoon Haiyan in 2013. A gradual reintroduction of species have commenced in 2024.
The Philippine Eagle inhabits primary dipterocarp forest, sometimes frequenting secondary growth and gallery forest. It feeds on a wide range of species, including the Philippine Flying Lemur (*Cynocephalus volans*) on Mindanao, endemic species of Cloud Rats on Luzon, palm civets (*Paradoxurus spp.*), snakes, monitor lizards, birds, bats and monkeys (Clark et al., 2015; Hurrell, 2014). Estimates based on the distribution of nests in Mindanao suggest that each pair covers an average of 133 km^2, including an average of 68 km^2 of forest (Miranda et al., 2008), although Sutton et al. (2023) revised this to a median size of 73 km^2 (minimum-maximum: 64-90 km^2). Birds form a monogamous bond for life, and a complete breeding cycle lasts two years, with successful pairs raising one offspring (Ibañez et al., 2003). Captive birds have reached more than 40 years of age (Clark et al., 2015).

The Department of Environment and Natural Resources – Biodiversity Management Bureau (DENR-BMB) and the Philippine Eagle Foundation (PEF) lead all efforts to conserve the Philippine Eagle at a national and regional level. As the country's lead agency for biodiversity conservation, DENR-BMB develops and enforces policies, manages protected areas, and coordinates conservation programs. It works closely with local communities, scientists, and partner organisations to protect eagle habitats, reduce threats such as hunting and deforestation, and promote awareness. Their efforts are closely coordinated with PEF, which was established in 1987 to protect and conserve the Philippine Eagle and its rainforest habitat. Based in Davao City (Mindanao Island), the foundation is a non-profit organisation dedicated to biodiversity conservation and sustainable development. Its mission is to ensure the survival of the Philippine Eagle through research, captive breeding, and community-based forest protection initiatives. PEF also works closely with local communities, governments, and partners to promote environmental education and foster a shared responsibility for preserving the country's rich natural heritage. In line with their statutory mission, DENR-BMB and the PEF initiated a PVA process led by the IUCN SSC Conservation Planning Specialist Group (CPSG), in order to address the current knowledge gap for the benefit of the species' conservation:

1. Identify and collate available demographic information on the Philippine Eagle.
2. Undertake a structured analysis of the threats to the Philippine Eagle.
3. Estimate the rate of the current decline in the three Philippine Eagle sub-populations
4. Understand which life history stages are more important determinants of the stability of Philippine Eagle populations.
5. Use population viability analysis (PVA) as a tool to identify threats to Philippine Eagle populations both in the medium- and long-term and their impacts on population stability.
6. Agree on which conservation interventions are more likely to be implemented in the future and quantify their likely impact on Philippine Eagle populations. Amongst these, the PEF has already expressed interest in exploring the potential impact of hunting, deforestation and bird flu, as well as the possible benefits of conservation translocation.
7. Carry out a participative conservation planning process to draw a plan for the conservation of the species, which is informed by the PVA results and inclusively discussed and agreed upon by all relevant stakeholders.

Vision

On 23rd and 24th April 2024, all experts and stakeholders gathered participants at the Seda Hotel, Quezon City, The Philippines, and together they developed a vision statement. The purpose of this exercise was to converge and consolidate the agreement amongstall stakeholders on what the ideal future for the Philippine Eagle would look like. This is a key step in the conservation planning process for the species. The vision statement serves as a guide for all the conservation actions subsequently identified.

Workshop participants were asked to imagine they were in 2075 and that all stakeholders have been doing their best and more to complete all actions required to conserve the eagle. They were asked to describe in a couple of sentences what the status of the Philippine Eagle would look like. All participants broke out into 5 different groups to work on this.

Each group presented and identified what it was they wanted to be included int eh final visions tatement and what needed to be eliminated. The final vision statement is:

"The Philippine Eagle is an integral part of Filipino biocultural heritage and identity. By 2075, there is a thriving population of the National Bird in diverse and balanced ecosystems, free from threats, co-existing with well-engaged human communities."

Threat Analysis

Working group participants (*in alphabetical order by surname*): For a full list of participants, please see Appendix I

Date & location: 23rd – 26th April 2024 at the Seda Hotel, Quezon City, The Philippines

Introduction

The initial step of the PVA process is understanding the threats to the focal species in the geographical area of interest and identifying those that are considered to have the greatest impact on the population's long-term viability. Workshop participants carried out a comprehensive semi-quantitative analysis of the different types of threats known to imperil the three remaining populations (in Luzon, Eastern Visayas, and Mindanao). In doing so, participants discussed which of the species' life history traits – reproduction, survival, dispersal, etc. –would be most affected by these threats. The process was carried out in three distinct and consecutive phases: 1) ranking of the known threat species (as per the latest draft of the action plan); 2) examining the mechanisms by which each of those threats may affect the species at a population level; and 3) understanding of the geographical distribution and expected severity of the threats.

Threat identification and ranking

The first objective was to agree on which anthropogenic factors are currently thought to be threatening Philippine Eagles and/or its habitat. Attendees were presented with the list of threats to the species, which had previously been identified in the draft species action. Attendees did not have any updates to make to the list, so it was agreed for the list to be organised into seven logical groups (Table 1).

Table 1. *List of threats to the Philippine Eagle (as identified by the existing draft action plan for the species) rearranged into seven logical categories (in bold).*

Habitat loss & degradation	
	Habitat Loss
	Treasure Hunting
	Intentional grass fire
	Timber poaching
	Charcoal making
	Human Encroachment
	Land conversion
	Mining
	Nest site destruction

Disturbance	
	Non-Timber Forest Products Disturbance breeding Eagles Noise pollution
Climate Change	
	Climate Change Extreme weather events
Direct Mortality	
	Accidental trapping Hunting of Eagles Accidental electrocution
Hunting of prey	
	Hunting of prey
Diseases	
	Zoonotic Diseases
Invasive Alien Species	
	Invasive Alien Species

The second objective was to rank the expected importance of such threats by region. A flipchart sheet with all seven threat categories was set up for each of the three populations. Each participant was provided with three "votes" (sticky dots) and asked to place those votes on each of the threat categories proportionally based on the following question:

> *"Which threats are (or have been) most directly responsible for a decline in the abundance of the population in your study area/region of interest?"*

Each participant was invited to 'vote' only for the population they had knowledge of or experience with. Those few individuals who had expertise on more than one population were given additional sets of three sticky dots for each additional population. It was stressed to participants that they should cast their votes based on *their own* research experience in *their* area of interest. This was to avoid the temptation to vote as others had voted (i.e. informational social influence).

This exercise allowed participants to identify and establish a broad prioritisation of the threats' expected impact for each population. Interestingly, although experts on the three populations worked independently, they produced a ranking of the threats which is almost identical (Table 2, Figure 1). *Habitat Loss & Degradation* were deemed to be the most consequential threats to the Philippine Eagle in all three areas, followed by *Direct Mortality*, *Disturbance*, *Hunting of the species' Prey*, *Climate Change*, *Diseases* and *Invasive Alien Species*, with the latter being of no concern in Luzon. The only difference was the way participants from the Eastern Visayas thought that *Climate Change* was more of a threat to the species than the *Hunting of Prey*.

Table 2. *List of the threats to the Philippine Eagle populations in order of importance based on the voting made by workshop attendants*

	Luzon	Mindanao	E Visayas
Habitat Loss & Degradation	36	31	12
Direct Mortality	19	15	7
Disturbance	11	15	4
Hunting of Prey	6	6	3
Climate Change	2	6	4
Diseases	1	2	1
Invasive Alien Species	0	1	1

Figure 1. *Ranking by the participants of the expected impactfulness of different threat categories on the three Philippine Eagle populations.*

Threat mechanisms, distribution and severity

Participants divided themselves into three groups according to their geographical area of expertise, namely Luzon, Mindanao and Eastern Visayas. Participants were asked to review the complete list of threats identified in the draft action plan (Table 1) in order of expected impact (Figure 1), and for each threat, they were asked to *a)* discuss the mechanisms by which the threat may affect the species' populations; *b)* identify published, unpublished data or anecdotal information on the subject; and c) collaboratively assess the expected severity of that threat i.e. Low / Medium / High. There was a plea to avoid discussing or exposing the identity of individuals or agencies behind some of the threats and to focus on the threats themselves. Each group appointed a note-taker and a spokesperson who would report to the plenary at the end of the exercise. All groups were facilitated by a CPSG representative. Finally, each group was provided with a diagram of the life cycle of the species (Figure 2) to aid the discussion on which life stage(s) may be most affected by any given threat.

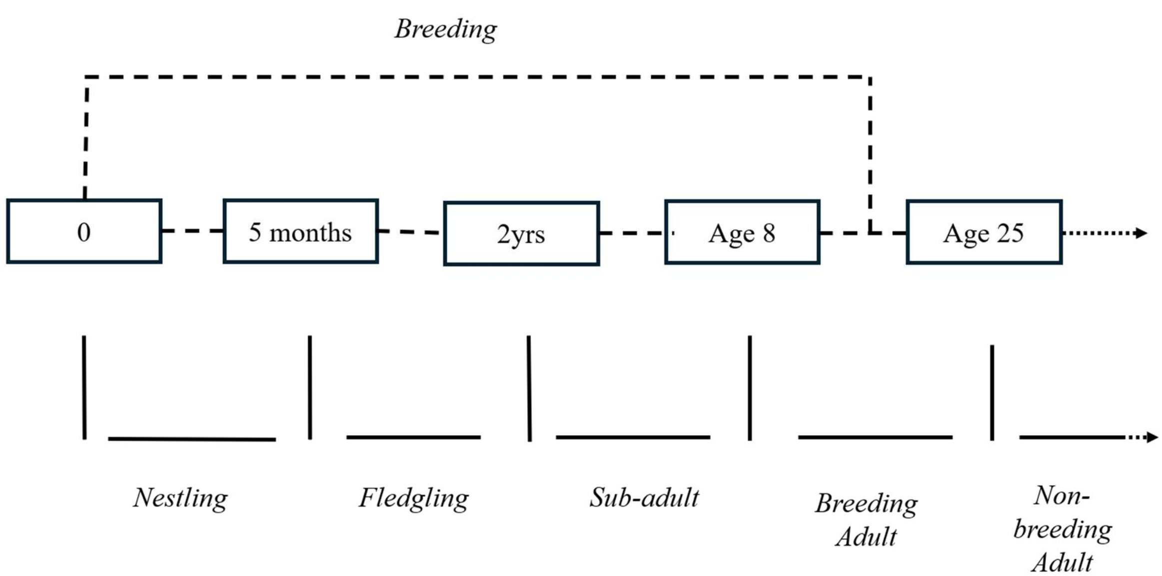

Figure 2. *Diagram of the Philippine Eagle life cycle with key life stages and their estimated duration.*

A complete list of participants is provided in Appendix I. Results of the expected severity for each threat are reported in Table 3.

Luzon

Habitat loss and degradation – (High)

Habitat loss and degradation take many forms in Luzon, namely, slash and burn practices, human encroachment (often with the added pressure of charcoal making in the vicinity of settlements), tourist development, and road building. All of these cause permanent changes to the landscape and are likely to result in the loss of suitable habitat (territories for hunting and breeding) for the Philippine Eagle. DENR holds data on forest land use, whereas some international NGOs, such as Conservation International and WWF, may have data on some protected areas only.

Treasure hunting – (Low)

It is a widespread belief that when the Japanese forces retreated from the Philippines in 1944-45, they hid considerable wealth in the forest (traditionally known as 'Yamashita treasure'). As a result of this, a number of privately funded search parties have been known to destroy habitat and cause disturbance as they follow tipoffs about where such treasure may be buried. This is thought to be an increasing trend, but disturbance is usually limited to a reasonably small area and likely to be temporary, i.e. the forest will regenerate in the medium- to long-term. Although exact quantification of this phenomenon is lacking, the Mines and Geosciences Bureau (MGB) and local governments have reports of individual incidents.

Mining – (High)

From the discussion among the participants, it was clear that two very different types of mining activities are ongoing in Luzon: large- and small-scale mining. In some cases, the two are linked because the exhaustion of large-scale mining enterprises may lead to successive smaller-scale operations. In other cases, small-scale prospective mining may pave the way for larger-scale enterprises. Large-scale mining is mostly for gold, copper and nickel (Sierra Madre and Zambales). These operations involve open pits with the associated production of considerable amounts of waste, dust, ground shaking, and noise. These areas are also subject to the development of access roads and housing for the workers who often live and hunt in the immediate surrounding areas. Although all of the above are causes of concern for the Philippine Eagle, there is no data available that documents a direct impact on the species. There is only some anecdotal information on the impact of noise on the presence of hornbills. There is also concern about the expansion of some of the existing mines as well as the opening of new ones. The MGB is in charge of releasing and recording mining permits. On the other hand, small-scale mining is often pursued in the same areas as large-scale mining when the latter stops being profitable. The provincial government may have information on instances of small-scale mining that may or may not be legal. All habitat modifications due to mining are likely to be permanent because of the destructive nature of this activity.

Land conversion – (High)

Besides the types of land conversion mentioned in the habitat loss section, a further cause of concern is the current or future plans for constructing large infrastructures such as dams, which will remove large portions of habitat suitable for the Philippine Eagles.

Intentional grass fires – (Low)

This is a specific practice limited to some areas where hunters purposefully set fire to forest clearings to renew the grass and attract deer for hunting. This does occasionally result in the accidental burning of the adjacent forest. This phenomenon is reasonably localised, and there is no evidence of a direct effect of these fires on the Philippine Eagles besides the obvious loss of suitable habitat in accidental forest fires. DENR is in charge of recording any instances of forest fires.

Timber poaching – (High)

The illegal harvest of timber is thought to pose a significant threat to the Philippine Eagle in three different ways: *a)* the large trees which are selectively felled are also the most suitable for the Philippine Eagle to nest on; *b)* despite being reasonably selective, tree felling often brings some level of habitat degradation in the immediate surroundings (e.g. temporary encampments, access paths/roads, etc.); and *c)* the noise of chainsaws and presence of people pose temporary but intense disturbance to the species. Timber poaching is often patchy and targets large trees in areas of mature forest. Although there is a high potential for the forest to regenerate where selective timber logging has been carried out, poachers tend to go back to the same areas time and time again. It was agreed that, although DENR holds reports of timber poaching, due to the illegal nature of this activity, this is likely to be an underestimate of the true magnitude of the phenomenon.

Non-timber forest products – (Medium-High)

Participants discussed the potential impact of a number of non-timber forest products. The harvest of rattan (Calamoideae) has been known to cause the destruction of nesting sites. Almaciga resin (from the dammar gum tree species - Dipterocarpaceae) is collected by felling the tree, which is also a known nest tree species for the Philippine Eagle. Finally, the harvest of honey is likely to cause disturbance to nest sites as both wild bees and Philippine Eagles prefer the same type of large trees.

Climate change and extreme weather events – (Medium)

Several potential consequences of climate change were discussed. Severe typhoons (category 4 and/or 5 on the Saffir-Simpson Hurricane Scale; Saffir 1973; Simpson 1974) are known to hit Luzon with some regularity. However, the timing of the Philippine Eagle breeding season in Luzon is still unclear, and therefore it is unknown how these typhoons may affect the breeding process. There is concern that sub-adults, as the most vulnerable of age classes, may be particularly affected by any extreme weather event. However, no information is available on the effects of typhoons on the Philippine Eagles of Luzon, and the participants' concerns are founded on knowledge from other areas. It is feared that extreme weather events such as typhoons may affect egg viability through sudden changes in temperature and humidity. Moreover, intense floods have been known to cause heightened soil erosion, mudslides, and, consequently, loss of forest area. Finally, changes in the length of the dry season are thought to affect prey availability.

Accidental trapping – (High)

A number of individuals are trapped accidentally in snares which are set out to capture other species (a common practice in many areas). Individuals which are caught in this way are sometimes sold or kept as pets. An unknown proportion of these is likely to end up at the Philippine Eagle Centre but rehabilitation of these individuals is often very difficult. Some of the Philippine Eagles caught in snares have been known to be eaten as a source of protein.

Hunting of eagles – (High)

Incidents of targeted killing of Philippine Eagles are less frequent. Some of these incidents are from farmers concerned for the welfare of their livestock (poultry mainly). These are normally shot with air guns, which are widespread and unregulated. In some cases, the motive behind this targeted shooting is unclear, but it is suspected that some do it for leisure (one confirmed case in Apayao).

Accidental electrocution – (Low)

Although the incidents of electrocution are known from other islands, there are no reports from Luzon. However, this is still a source of concern as the electrification reaches some rural areas where electricity has not been provided.

Hunting of prey – (High)

Some of the Philippine Eagle's prey species are known to be hunted by humans, and some of these are threatened in their own right (e.g. Sierra Madre Forest Monitor *Varanus bitatawa*). This is a source of concern as this is thought to affect Philippine Eagles in periods when it is under particular anthropogenic pressure or at particularly vulnerable life stages e.g. breeding. DENR holds records of the abundance of some of these species.

Diseases – (Medium)

There are a number of diseases which are known to potentially affect the Philippine Eagle but none of them has, thus far, been recorded in the wild. Despite this, there is apprehension that a particularly violent outbreak could potentially have a great impact on the Luzon population. *Virulent Newcastle disease* has been recorded in captivity, and there is fear that poultry farms in villages near Philippine Eagle territories may be a source of spread. *Aspergillosis* is a common but non-pathological fungal infection which lingers in nests but can become pathological and possibly deadly in birds under physical and environmental stress (known cases in captivity). It is known to be a cause of mortality in captive birds. *Avian influenza* has not yet been recorded among Philippine Eagles but the vicinity of poultry farms is a reason for concern.

Invasive alien species – N.A.

There are no invasive species in Luzon which are likely to impact Philippine Eagle populations.

Mindanao

Habitat loss and degradation – (High)

In Mindanao, in most cases, habitat loss and degradation are due to human encroachment, i.e. people settling in the Philippine Eagle habitat and pursuing subsistence farming. This results in the removal of suitable habitat, affecting both the success of nearby nests and limiting the future availability of sites. Maps of forest cover held by DENR are likely to hold useful data on the rate of such habitat loss.

Treasure hunting – (Low)

Like in Luzon, Mindanao has had a number of instances where patches of forest were cleared by groups of people in search of treasures allegedly left behind by the Japanese occupation in World War II. The search sites are mainly within river easement areas, and the habitat disruption is often very localised, carried out with low technology implements, and, as a consequence, the impact of these activities is thought to be low and very short-term.

Mining – (Medium)

In Mindanao, mining activities mainly target gold, copper, nickel and limestone. As for Luzon, mining is carried out at two different scales: artisanal mining, which is at a small scale and mostly illegal, and large-scale open pit mining. The latter is thought to also cause lots of disturbance in different ways (see *§ Luzon, Mining*), and it is known to occur in the Philippine Eagle habitat.

Land conversion & Intentional grass fires – (High)

Similarly to encroachment, land conversion (including intentional grass fires) is mainly due to agriculture, urbanisation, road building and tourism. Such habitat loss is likely to impact Philippine Eagles at all life stages– including loss of nest sites, nestlings, fledglings, etc.

Timber poaching – (Medium)

Small-scale illegal logging occurs in Mindanao. Mostly, this involves the removal of specific individual trees, which often are the preferred nesting trees for the Philippine Eagle. Such activities are widespread across the island. Although these activities are carried out all year round, they tend to increase in frequency during the dry season, with a consequent greater risk for nestlings.

Charcoal Making – (Low)

Charcoal making in Mindanao is typically not made with large trees, i.e. suitable for nesting. Charcoal production normally entails the use of smaller trees, which are planted especially for harvest. Most charcoal-making activities are illegal, and they occur across the island. They tend to be carried out mostly on forest edges, with no consideration of the potential disturbance to the Philippine Eagle.

Non-timber forest products – (Low-Medium)

The key non-timber forest product mentioned by participants was rattan. Rattan is a vine and, to facilitate harvesting, the supporting trees are sometimes felled. This can disturb nesting Philippine Eagles if they are present in the area. This kind of activity is regulated by a permit system in some regions, whereas it is illegal in other areas.

Climate change and extreme weather events – (Medium-High)

In Mindanao, climate change is thought to be affecting the Philippine Eagle in a number of ways. An alleged increased frequency of extreme weather events, such as typhoons and strong rain, is said to be damaging large nesting trees. Higher rainfall levels are also thought to diminish hatching success due to improper incubation and possibly causing a delay in the breeding season. As in other islands, anecdotal data shows an increase in the dryness of the dry season, which, in turn, increases the frequency and severity of wildfires. Overall, in the medium- to long-term, climate change is thought to cause a broad change in canopy cover and prey density.

Accidental trapping – (High)

Philippine Eagles have been caught by mistake in traps originally set to catch wild boar or other ground-dwelling edible species. Sub-adults and adults are the most vulnerable to this type of bycatch. Males or females seem to be equally susceptible to this threat, which is spread across of Mindanao Island. The Philippine Eagle Centre is a good source of data on this specific threat.

Hunting of eagles – (unspecified)

There are cases in which Philippine Eagles are intentionally targeted. Mostly, this is either by accident (mistaken for other species that may taste better) or with the intent of protecting livestock. There have been cases in which trapped birds were sold for food. Younger birds seem to be most vulnerable to this threat, whereas males and females are equally targeted.

Accidental electrocution – (Medium)

There have been two instances in which Philippine Eagles have succumbed to electrocution by perching on power lines. Both these incidents involved sub-adults, one of which had been recently released into the wild from captivity (data from the Philippine Eagle Foundation).

Hunting of prey – (Medium-High)

Humans are thought to be reducing the availability of prey species for the Philippine Eagles. Amongst these preferred species are deer, long-tailed macaques (*Macaca fascicularis*), flying foxes, wild pigs; although civets and, to a lesser extent, flying lemurs and snakes are also consumed by Philippine Eagles. The lack of prey is likely to reduce breeding success and push individuals to venture out of their optimal habitat, which, as a consequence, would make them more susceptible to entering into negative interactions with humans.

Disturbance of breeding eagles – (Medium)

Disturbance of breeding eagles can happen by means of many of the other threats analysed here. A particular case is the armed conflict with leftist rebels (which have been known to include the use of artillery), which is thought to have caused significant disturbance to Philippine Eagles and loss of their habitat. On the other hand, conflict decreases the chances of people settling in these areas, providing increased protection for the Philippine Eagle.

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Noise pollution – (Low-Medium)

Amongst the potential causes of noise pollution, participants listed: road construction, tourism, logging and mining. Military activities are also a source of significant noise pollution (see *§ Mindanao, Disturbance of breeding eagles*). It is thought that noise is likely to impact chicks more than adults.

Diseases – (N.A.)

Not discussed.

Invasive alien species – (N.A.)

Not discussed.

Eastern Visayas

The Eastern Visayas include the islands of Samar and Leyte, 13,428.8 km^2 and 7,367.6 km^{2,} respectively. The forest in Samar extends up to 600 m.a.s.l., whereas in Leyte it exceeds 1,000 m.s.l. In the case of Leyte, where there currently are no Philippine Eagles, the below assessment refers to either the past or potential severity and impact on the species.

Habitat loss and degradation – (High)

Habitat loss affects all types of forests in the Eastern Visayas. In Samar, slash-and-burn agriculture is used to convert the land into coconut and rice plantations. These are normally implemented in patches of 1-2 ha, but not on limestone. In Leyte, slash-and-burn is practised mainly to grow coconut and corn plantations. The size of the cleared areas is similar to that in Samar, but there is much more of an incremental expansion from the edges of human settlements. Habitat loss in the Eastern Visayas is thought to be a threat to all life stages of the Philippine Eagle and affects all of its ecological needs.

Charcoal making – (Medium/Low)

Charcoal making is practised in Samar but not in Leyte. Such activity is carried out mostly where there is no possibility of agricultural development. It tends to be of high intensity in areas around nesting sites and of medium intensity across the rest of the islands. This is thought to affect most of the Philippine Eagle's life stages.

Timber poaching – (High/Medium)

In Samar, the illegal and selective harvest of large trees is mostly for boat- and furniture-building purposes. In these cases, only trees of particularly large sizes are selected. On the other hand, in Leyte, timber poaching is mainly for domestic use, i.e. for building houses. This type of timber harvest is thought to be selecting potential Philippine Eagle nest trees and therefore directly affecting breeding opportunities.

Human encroachment – (Medium)

The threat from human encroachment and housing development is very similar in both islands, and they always tend to occur at the edge of existing settlements. The new development is normally structural and dependent on the local family size and their growth. Typically, the impact of this type of development is small (approximately 1 ha) but widespread (1 ha for each family). This type of development is thought to be particularly dangerous for sub-adult and adult individuals who may venture into new areas for hunting.

Treasure hunting – (Low)

Treasure hunting is not an issue in Samar and is extremely uncommon in Leyte, with only one confirmed case around a river, i.e. not affecting a forest area. The impact of this type of activity on Philippine Eagles is therefore deemed to be negligible or non-existent in the Eastern Visayas.

Land conversion – (High)

There is a concern for large-scale land conversion for infrastructure development, specifically plans for the opening of new hydropower plants on both islands, and the building of annexed roads, which are likely to affect hundreds of hectares. This is likely to impact all ecological needs of the Philippine Eagle, with a domino effect exacerbating other threats.

Intentional grass fire – (Low)

Intentional grass fire is a threat not relevant to their Eastern Visayas as the habitat does not lend itself to this practice.

Mining – (Low)

Mining activities in the Eastern Visayas are small-scale and unlikely to impact the Philippine Eagle habitat. In Samar, mining is limited to the smaller islands, whereas in Leyte is practised mostly along the coastline for the extraction of black sand.

Nest site destruction – (Medium/N.A.)

This is mostly due to charcoal making in Samar, whereas no nest site has yet been found in Leyte.

Accidental trapping – (Low/Medium)

There have been some incidents of accidental trapping in Samar. These are normally of bycatch with traps set for wild pigs, deer or jungle fowl (one case of a sub-adult in 2019). On Samar, the Samar Island Natural Park is a protected area and benefits from a form protection and enforcement against trapping, with concessions made for IP groups. Trapping for pigs and deer is also very frequent in Leyte, which is not a protected area. However, the impact on Philippine Eagles is unknown as the species has not been seen since 2013. There is, however, historical evidence of accidental trapping in the area. Accidental trapping is thought to impact mostly sub-adults as they are most inexperienced and engage in explorative dispersal.

Hunting of eagles – (Medium/High)

The direct targeting of Philippine Eagles is known from Samar. Some of these cases stem from farmers trying to protect the livestock, but a percentage of the incidents are thought to be for recreational purposes. Similar to Luzon, this involves airguns, which are widely available and unregulated. Airguns are widely used in Leyte as well. Participants agreed that there is a very low awareness of the importance of the Eagle in Leyte, possibly due to the limited experience with the species.

Accidental electrocution – (Medium/Low)

There are two known incidents of electrocution of Philippine Eagles, but none of them occurred in the Eastern Visayas. The potential of such a threat is highest in Samar because of the higher levels of development. However, participants agreed that the true amount of area overlap between the powerline and the Philippine Eagle habitat is indeed very low. Accidental electrocution is thought to be a threat mostly for inexperienced sub-adults.

Non-timber forest products – (Low)

The forests of Samar and Leyte are used to harvest a number of non-timber products, most notably rattan, hemp, agarwood, seedlings, honey, medicinal plants, ornamental plants, tubers and roots for human consumption. In all cases, extraction methods are thought to be non-disruptive and unlikely to cause disturbance to Philippine Eagles. In protected areas, collection is regulated by a permit system.

Disturbance of breeding eagles – (Low)

The extent of disturbance to breeding eagles is low in the Eastern Visayas. One case occurred in Samar where a pair attacked someone who was disturbing the nest. On the other hand, nest trees are very hard to find. As previously mentioned, there is no evidence of nesting Philippine Eagles in Leyte to date.

Noise pollution – (Low)

In the Eastern Visayas, noise pollution may stem from timber farms in Samar, but these tend to be far from the Philippine Eagle habitat. Also, the construction of hydro and solar panel plants in Samar is seen as a potential cause of disturbance. Noise is thought to most likely affect breeding adults i.e. resulting in the abandonment of the nest or the chick.

Climate change and extreme weather events – (High)

The effects of climate change are predicted to take different forms in the Eastern Visayas. An increase in the intensity of typhoons has been observed. Sightings of the Philippine Eagle have reduced significantly since Typhoon Yolanda, which is also thought to have caused the extirpation of the species from Leyte. Typhoons are thought to cause direct mortality, loss of suitable habitat and most likely reduce the availability of prey. Another consequence of climate are longer and hotter dry seasons. The extreme heat is likely to reduce productive success and prey availability, whereas there is concern that drought may cause abandonment of the nest, reduced prey availability and exacerbate the risk of forest fires.

Hunting of prey – (Medium)

The potential impacts of hunting the Philippine Eagle's preferred prey species are thought to be very similar across the Eastern Visayas. Amongst the prey items which are also targeted by hunters are long-tailed macaques, monitor lizards, civets, snakes, small raptors, wild pigs, hornbills, owls, rodents, flying lemurs, deer and flying foxes. The lack of prey items is thought to impact every life stage, particularly when they are raising chicks. Philippine eagles can be flexible in the type of prey they target. However, this also means that if prey items are scarce, they will venture further afield and potentially target livestock (mainly poultry), increasing the risk of disease and negative interaction with humans.

Diseases – (High)

The risk of disease is thought to be the same for Samar and Leyte. No disease survey has been carried out for the Eastern Visayas, so concerns are mostly derived from knowledge from other islands. *Avian influenza*, *virulent Newcastle disease* and *aspergillosis* are the key diseases (see *§ Luzon, Diseases*), and there is growing concern about emerging infectious diseases.

Invasive alien species – (Medium)

In both Samar and Leyte, *Piper aduncum* prevents forest regeneration, and this is thought to affect all life stages of the Philippine Eagle. Another invasive species of concern is the spread of Mahogany trees in the forest.

Table 3. *Expected severity (Low/green, Medium/orange, High/red) of the key threats to the Philippine Eagle in the populations of Luzon, Mindanao and Eastern Visayas*

<table>
<tr><th>Threat</th><th>Luzon</th><th>Mindanao</th><th>Samar</th><th>Leyte</th></tr>
<tr><td>Habitat loss</td><td rowspan="3">High</td><td>High</td><td>High</td><td>High</td></tr>
<tr><td>Charcoal making</td><td>Low</td><td>Medium</td><td>Low</td></tr>
<tr><td>Human encroachment</td><td>High</td><td>Medium</td><td>Medium</td></tr>
<tr><td>Treasure hunting</td><td>Low</td><td>Low</td><td>Low</td><td>Low</td></tr>
<tr><td>Timber poaching</td><td>High</td><td>Medium</td><td>High</td><td>Medium</td></tr>
<tr><td>Land conversion</td><td>High</td><td rowspan="2">High</td><td>High</td><td>High</td></tr>
<tr><td>Intentional grass fires</td><td>Low</td><td>Low</td><td>Low</td></tr>
<tr><td>Mining</td><td>High</td><td>Medium</td><td>Low</td><td>N.A.</td></tr>
<tr><td>Nest site destruction</td><td>High</td><td>?</td><td>Medium</td><td>Low</td></tr>
<tr><td>Non-timber forest products</td><td>Medium
High</td><td>Low
Medium</td><td>Low</td><td>Low</td></tr>
<tr><td>Disturbance breeding eagles</td><td>High</td><td>Medium</td><td>Low</td><td>Low</td></tr>
<tr><td>Noise pollution</td><td>Medium</td><td>Low
Medium</td><td>Medium</td><td>Low</td></tr>
<tr><td>Climate change</td><td>Medium</td><td rowspan="2">Medium
High</td><td>High</td><td>High</td></tr>
<tr><td>Extreme weather events</td><td>Medium</td><td>High</td><td>High</td></tr>
<tr><td>Accidental trapping</td><td>High</td><td>High</td><td>Low</td><td>Medium</td></tr>
<tr><td>Hunting of eagles</td><td>High</td><td>?</td><td>Medium</td><td>High</td></tr>
<tr><td>Accidental electrocution</td><td>Low</td><td>Medium</td><td>Medium</td><td>Low</td></tr>
<tr><td>Hunting of prey</td><td>High</td><td>Medium
High</td><td>Medium</td><td>Medium</td></tr>
<tr><td>Diseases</td><td>Medium</td><td>?</td><td>High</td><td>High</td></tr>
<tr><td>Invasive Alien Species</td><td>N.A.</td><td>?</td><td>Medium</td><td>Medium</td></tr>
</table>

Population Modelling

The *VORTEX* computer model is a PVA simulation model of the effects of deterministic forces as well as demographic, environmental, and genetic stochastic events on wild populations. *VORTEX* models population dynamics as discrete sequential events (e.g., births, deaths, sex ratios among offspring, catastrophes, etc.) that occur according to defined probabilities. The probabilities of events are modelled as constants or random variables that follow specified distributions. The package simulates a population by stepping through a series of events that describe the typical life cycles of sexually reproducing, diploid organisms.

PVA methodologies such as the *VORTEX* system are not intended to give absolute and precise 'answers', since they are projecting the interactions of many randomly fluctuating parameters used as model input, and because of the considerable uncertainty, we observe in typical wildlife population demography datasets. Because of these limitations, many researchers have cautioned against the sole use of PVA results to promote specific management actions for threatened populations (Beissinger & McCullough, 2002; Ellner et al., 2002; Lotts et al., 2004; Ludwig, 1999; Reed et al., 2002). Instead, the true value of an analysis of this type lies in the assembly and critical analysis of the available information on the species and its ecology, and in the ability to compare an array of possible scenarios theorised through the methodical variation of key parameters in the demographic model of a given species i.e. sensitivity analysis (Mills & Lindberg, 2002). PVAs can be extremely useful to conservation biologists as a secondary source of analysis if results are conservatively interpreted in terms of uncertainty (Reed et al., 2002).

The *VORTEX* system for conducting population viability analysis is a flexible and accessible tool that can be adapted to a wide variety of species types and life histories as the situation warrants. The program has been used around the world for both teaching and research applications and is an accepted method for assisting in the definition of practical wildlife management methodologies. Nonetheless, the interpretation of the output should depend upon the best available knowledge of the biology of the species in its habitat, the environmental conditions affecting it, and possible future changes in these conditions. For a more detailed explanation of *VORTEX* and its use in population viability analysis, refer to Lacy (2000) and Lacy, Miller, and Traylor-Holzer (2021)

POPULATION

Population refers here to the total number of individuals of the same species (i.e. capable of interbreeding) within a specific geographical or ecological boundary, i.e. sharing common characteristics and residing in a particular habitat with minimal or no fragmentation (Wells & Richmond, 1995).

Baseline Input Parameters for Stochastic Population Viability Simulations

Much of the demographic data used as input to the Philippine Eagle population dynamics models is derived from the published literature and some unpublished data which were made available by the species' experts at different stages of the process. A prototype of the baseline model was presented for feedback in a dedicated session at the PVA workshop held in Quezon City (23rd-26th April 2024) — for a complete list of participants, please see *Appendix I*.

Baseline population model

The baseline population model was developed based on the best available (published and unpublished) knowledge of the biology and demographics of the species. The model and its parameters were subjected to the scrutiny of and agreed upon by the experts consulted at the workshop and in a number of online meetings. However, the lack of data on a number of crucial parameters (most notably mortality rates, population sizes and trends) meant that it was not possible to create a baseline model that accurately and realistically represents observed growth rates of existing Philippine Eagle populations. Insteada series of baseline ranges for demographic parameters were gathered to be used in subsequent sensitivity testing analyses.

A word of warning about the baseline population parameters

The baseline population parameters gathered and presented here is a representation of the biological and demographic potential of the species in ideal/theoretical conditions that are devoid of natural and anthropogenic threats. This, by no means, is not a realistic depiction of any specific real-world population.

Populations and Population Growth Rates

The target unit of PVA is a 'population', which is here defined as a group of individuals of the same species inhabiting a specific geographic area that is not fragmented. This may include subpopulations which have the possibility of exchanging individuals and interbreeding i.e. metapopulation (e.g. individuals in Leyte and Samar, if both islands were occupied by eagles). This analytical approach serves as a bridge between theoretical ecological principles and practical conservation strategies. The population thus defined as a unit does not experience any emigration or immigration unless human-assisted i.e. translocations and reintroductions.

In this sense, the Philippine Eagle has three distinct populations inhabiting three discrete areas, namely Luzon Island, the Eastern Visayas Islands and Mindanao Island. Although the population in the Eastern Visayas is currently limited to Samar Island (7 breeding pairs; *unpublished data*), it used to be present on the island of Leyte as well and plans to relocate some (target of 20 individuals) individuals are underway. Of the three, the population in Mindanao is the most studied and thought to be the most abundant (see *§ Initial Population Size*).

In addition to these three populations, a fourth ex situ population was discussed but not included in the PVA. There are three captive facilities which currently host Philippine Eagles. One adult female is held at the 'Bird Paradise' in Singapore. She was loaned with her mate, who died in 2023. One old individual is kept at the DENR facility in Quezon City, Luzon. By and large, the most significant captive population is that hosted by the Philippine Eagle Centre in Davao City, Mindanao, which serves as both a rehabilitation and breeding facility and has been operating since 1987. The centre currently holds 35 Philippine Eagles, of which six are active and successful breeders i.e. 3 pairs. All of the Philippine Eagle Centre individuals arrived at the centre with some degree of injury and most of them cannot be released back to the wild. This is also true for a number of captive-bred birds which are imprinted to humans. Only three birds were released have ever been released to the wild, and all of the reintroductions were unsuccessful for different reasons. The captive population is currently not self-sustaining.

To date, there are no systematic monitoring schemes consistent and rigorous enough in their methodology to be able to infer the trend over time for any of the wild populations. Since 1993, DENR has been coordinating Regional Eagle Watch Teams, but due to inconsistencies in population survey design over time, it is not possible to calculate a reliable estimate of the finite population growth (λ) rate for the species in the wild. Thus, the population models were constructed with different hypothetical population growth (λ) values depending on the purpose of the analysis at hand (*see below*).

Breeding System

The Philippine Eagle displays a **long-term monogamous** breeding system in which a female and a male pair for life (Gonzales et al., 1968; Kennedy, 1977). As a pair is formed, it will hold a territory of a median size of 73 km2 (minimum-maximum: 64-90 km2; Sutton et al., 2023). The pair, wherever possible, will be site-faithful. Breeding individuals are known to pair again if their mate dies.

Age of First Reproduction

VORTEX considers the age of first reproduction as the age at which the first offspring are produced, not simply the onset of sexual maturity. Unpublished evidence from the Philippine Eagle Centre shows that captive adult females normally start reproducing at eight years of age (range 8-10 years old). On the other hand, information on wild populations is minimal and possibly unreliable. Krupa (1989) estimated wild Philippine Eagles to start breeding at 6-8 years of age, but this seems to be based on knowledge of raptors in general rather than on original data on the species. Workshop participants agreed that '**8 years of age**' is likely to be an accurate estimate of the age of first reproduction for both captive and wild birds.

Age of Reproductive Senescence

In its simplest form, *VORTEX* assumes that animals can reproduce (at the normal rate) throughout their adult life until a set '*Maximum age of reproduction*'. Reproductive success declines with age in many long-lived species such as *Acciptiridae* (Newton & Rothery, 1997; Saether, 1990). However, this knowledge relies on long-term demographic studies which are lacking for most species. On the other hand, the extensive efforts of breeding Philippine Eagles in captivity have shown that most birds stop reproducing at the **age of 25** (J. Ibañez *pers com.*), and this was the value used for the model in *VORTEX.* A specific simulation analysis was carried out in order to better understand the importance of an early stop in reproduction compared to the potential maximum lifespan (see below *§ Senescence)*

Maximum Lifespan

The Philippine Eagle is a long-lived species and has the potential to live **40 years of age**, at least in captivity. This is something which has been observed repeatedly in captivity (Alvarez, 1970; Bronzini, 1978), where the maximum age ever recorded is 56 years (J. Ibañez, *pers. comm.*). On the other hand, there is no information on how long the species may be able to live in the wild.

The baseline model was set with a conservative maximum lifespan of 40 years old, assuming that the contribution of old non-reproductive individuals (see *§ Age of Reproductive Senescence*) to the medium- and long-term health of the population is of limited impact anyway.

Offspring Production

A pair will normally lay **one egg** (Collar et al., 2001). There are known cases of females producing two eggs in captivity (Grossman & Hamlet, 1964; Kennedy, 1981; Wylie, 1974), but this remains a very rare occurrence where, normally, only one chick survives. Workshop participants agreed that the PVA model should allow for pairs to lay only one egg. Incubation is c.60 days (Gonzales et al., 1968), followed by a five-and-a-half-month nestling period and a dependency period of up to six and a half months (Kennedy, 1981). Because pairs will breed every two years (Collar et al., 2001). **Male: Female sex ratio at birth is 1:1**.

Male Breeding Pool

In many species, some adult males may be socially restricted from breeding despite being physiologically capable. This can be modelled in *VORTEX* by specifying a portion of the total pool of adult males that may be considered available for breeding each year. Observations of the Philippine Eagles in the wild suggest that there are no such behavioural mechanisms at play in this species and all adult males are equally capable of pairing with an adult female when necessary. We therefore set the probability of an adult male entering the breeding pool as **100%.**

Mortality

Information on the Philippine Eagle's mortality rates for different age classes in the wild is sparse. Krupa (1989) estimated mortality between 0 and 2 years to be 50-70% in disturbed habitats and 20-40% in undisturbed ones, whereas mortality of subadults (from age 2 to adulthood at age 8) was expected to be 40-70% and 30-50% in disturbed and undisturbed habitats, respectively. However, these estimates were not supported by sufficient data and confidence in these values amongst the workshop participants was low. Miranda et al. (2000) found the cumulative mortality rates over the first two years of age to be ~25% i.e. **juvenile mortality (years 0-2) = 13.5% per year**.

Many of the individuals released into the wild over the last few years have been provided with satellite trackers (*n*=16; 2 adults and 14 aged 2-5 years old). However, it is hard to draw conclusions on the natural mortality of the species, as these are individuals likely to be more vulnerable due to their rehabilitation history. Of these, eight individuals either died of anthropogenic causes (4), disappeared (2) or had to be re-trapped due to further injury. Twelve more individuals (six adults and six subadults) were trapped in the wild and released again with a satellite tracker. Of the subadults, one went missing and four died of anthropogenic causes, whereas the remaining seven individuals were still alive at the time of writing or at the time of battery failure. These studies offer an insight into the potential mortality rates in nature, but the sample size is too small to offer conclusive data. Nonetheless, the workshop participants agreed that the *subadult life stage is expected to be the most vulnerable* (most of the admissions in the rescue centre are from this cohort) because, at this age, individuals tend to disperse and explore potentially unsafe areas. This distribution of mortality across age classes is inconsistent with what has been documented in other large eagle species, where the highest mortality rates are observed in the first (or first two) years of age (Newton et al., 2016).

Plausible minima/maxima for both sub-adult and adult mortality were identified in consultation with species experts. To investigate the relative importance of each of these parameters while acknowledging the comparative uncertainty in the true value, an adjusted version of the ranges provided by experts was used to carry out a demographic sensitivity analysis (see *§ Demographic Sensitivity Analysis*) i.e. **sub-adult mortality (years 3-7) = 4.4-44% per year** and **adult mortality (years ≥8) = 1-10% per year**.

VORTEX requires a measure of environmental variation (EV) to model the yearly fluctuations in the probabilities of survival that arise from random changes in environmental conditions. EV impacts all individuals in the population simultaneously. However, none of the sources provided a measure of interannual variation of mortality; thus, arbitrary values of EV were applied for mortality across age classes (Table 4).

Catastrophes

No catastrophes were included in the baseline model or successive analyses as data is not available on the frequency of these events nor on their impact on the species.

Inbreeding Depression

There is currently no data on the mode of action of inbreeding depression in wild Philippine Eagle populations, or even if inbreeding depression exists at all. Therefore, it is impossible to quantify the role this process may play in the three populations taken into consideration. Moreover, the species was found to have a high genetic comparable with that of other threatened and non-threatened accipitrid species (Luczon et al., 2014). Nevertheless, due to the concerns of inbreeding in small island populations (Frankham, 1996), the potential importance of inbreeding (expressed as the number of lethal equivalents was tested in the sensitivity analysis (see *§ Demographic Sensitivity Analysis*) i.e. a range **between 0 and 10 lethal equivalents**. Please note that *VORTEX*'s default value is 6.29 lethal equivalents, based on O'Grady et al. (2006). In some cases, a measure of change in gene diversity over time was used to evaluate results from some of the scenarios. *VORTEX* calculates 'gene diversity' (or 'expected heterozygosity') based on allele frequencies at simulated neutral loci.

Mate Monopolisation

In each reproductive season, **100%** of adult males are assumed to be available to breed as long as they are of breeding age.

Carrying Capacity

The carrying capacity (*K*) for a given habitat patch defines an upper limit for the population size, above which additional mortality is imposed randomly across all age classes in order to return the population to the value set for *K*. Carrying capacity is typically very difficult to estimate in the field for any species. *VORTEX*'s default way of implementing carrying capacity is by a probabilistic truncation across all age classes when the indicated *K* is exceeded at the end of each simulation year i.e. additional mortality is imposed so that after the truncation, the expected population size is *K*.
Due to a lack of data on the maximum total population size that different areas can sustain, the baseline model is designed to allow unrestrained growth of the population beyond its initial size, i.e. *K* was set to an overgenerous purely theoretical 10,000 individuals.

However, a recent study has produced some credible estimates of a different type of carrying capacity, namely the maximum number of breeding pairs for each of the three populations, based on remote sensing, habitat modelling and mean territory size (Sutton et al., 2023). This functional limitation to the number of individuals which can successfully breed in an area was implemented in the model as a required criterion for females to pair with males i.e. the male is of breeding age, not yet paired and there are vacant territories in the area (based on a maximum indicated in the model). To better understand the relative impact of *K* expressed as the total number of territories on the medium- and long-term viability of populations, a range of different values was included for this parameter (***K* = 100-1,000 available territories**) in the demographic sensitivity analysis (see *§ Demographic Sensitivity Analysis*).

Initial Population Size

At the time of writing, there are no population estimates for the species populations, and where information is available, it is often expressed in terms of breeding pairs rather than total population size. The IUCN Red List gives a coarse global population estimate of 180-500 mature individuals based on Bueser et al. (2003). Workshop participants agreed that the population in

Mindanao is likely to be at carrying capacity (~233 pairs; see *§ Carrying Capacity*) i.e. all available breeding territories are occupied as pairs attempt to breed in sub-optimal and fragmented habitats. The island of Samar is thought to have seven breeding pairs, whilst the few individuals which were present on Leyte are now thought to be absent (*unpublished data*), probably due to the effects of Typhoon Haiyan, known in the Philippines as Super Typhoon Yolanda. Population estimates for the island of Luzon are not available. To understand the importance of the initial population size in relation to other parameters, a range of different sizes (**initial population size = 50-500 individuals**) was tested as part of the sensitivity analysis (see *§ Demographic Sensitivity Analysis*).

Iterations and Years of Projection

All population projections (scenarios) were simulated 500 times. Each projection extends to 100 years, with demographic information obtained at annual intervals. 100 years was deemed a suitable timescale to evaluate the long-term viability of populations for long-lived species such as the Philippine Eagle. Table 5 shows the demographic input parameters for the baseline model. All simulations were conducted using *VORTEX* version 10.5.6. (Lacy and Pollack 2022).

Table 4. *Demographic input parameters for the baseline VORTEX model for the Philippine Eagle across its native range. See the accompanying text for more information. Where values were not available range values (*) used in demographic sensitivity analysis are provided*

Model Input Parameter	**Baseline value**
Breeding System	Long-term monoagamous
Age of first reproduction ♂/♀	8
Maximum age of reproduction ♂/♀	25
Inbreeding *(number of lethal equivalents)*	0-10*
Annual % adult females reproducing	100%
Overall offspring sex ratio	1:1
Adult males in the breeding pool	100%
% annual mortality (%EV)	
Juvenile (0-2) ♂/♀	13.5 (5)
Sub-adult (3-7) ♂/♀	4.4(2)-44(2)*
Adult (≥8) ♂/♀	1(0.5)-10(0.5)*
Catastrophe	No
Initial population size	50-500*
Carrying Capacity (*number of territories available*)	100-1,000*

Research questions

After discussing the functionalities of PVA and its potential use as a diagnostic tool to help inform conservation management, workshop participants were asked to write one or more questions that they would like to see answered and/or explored by the PVA. All participants had Post-it notes available where they could write their questions (one per note) and then stick them to a shared board. Workshop facilitators grouped the Post-it notes in broad groupings and provided some feedback on where and how PVA may be best used. A large number of questions were aimed at having a better understanding of how PVAs work. However, some key enquiry avenues emerged from this exercise, which can broadly be summarised by the following questions:

- What is the predicted long-term trajectory of the Philippine Eagle population if the **status quo** is maintained (including current human population growth)? i.e. are our current efforts enough to ensure the long-term survival of the species?
- What is the impact of the loss of habitat due to **deforestation** or changes in land use? What kind of **reforestation** efforts are needed to counteract such impacts? How much **area of suitable habitat** do we need to secure the long-term viability of the three populations?
- What is the long-term impact of specific **threats** such as poaching or habitat loss?
- What may be the impact of an **epidemic** on the population?
- More specifically, what is the relative difference between losing males and females?
- What are the **minimum** and the '**recommended' population size** to ensure the long-term viability of the Philippine Eagle across its range?
- How many individuals need to be **reintroduced** in a suitable vacant habitat (e.g. Leyte) to establish a self-sustaining and growing population?
- How many individuals need to be **reintroduced** in the wild to offset the losses due to anthropogenic causes, e.g. poaching?
- How many individuals need to be **taken from the wild** to captivity to establish a self-sustaining and growing *ex situ* population?
- How is **gene diversity** maintained or lost in the above scenarios?

Data availability on demographic parameters allowed for direct investigation of only some of the above questions.

Discussion and Endorsement of the Results

The results of the analyses were sent to workshop participants for their review and feedback. All comments and feedback received were incorporated into this revised version of the report. The results were also presented, discussed and eventually endorsed by the participants of the Philippine Eagle planning workshop (Davao City, 1-4 September 2025, see Appendix II for full list of participants).

Demographic sensitivity analysis

Multi-factor Sensitivity Testing

During the development of the baseline input dataset, it became apparent that many of the key life history traits of the Philippine Eagle are still unknown. Where such information is available for captive individuals, it is often from small sample sizes. Because of this, a sensitivity analysis approach was used to investigate the relative importance of selected parameters (based on preliminary explorative analyses) to the short- and long-term viability of the wild populations. Thus, none of the models subsequently developed was a representation of a specific 'real world' population. A total of 1,000 iterations were run for each of 55 randomly selected combinations of input parameters, with each parameter sampled from specified ranges (Table 5). The selected parameters were evenly spaced across their respective ranges, with the sampling done according to the 'Single-Factor' option, where each parameter is varied across its range while holding all the other parameters at the base values. This option provides a way to test each parameter independently without being affected by interactions among parameters. This sampling method provides good levels of statistical power for determining the effect of each sampled parameter on the output metric of interest – in this case, population growth rate.

Table 5. *Parameter values included in the demographic sensitivity analysis*

	Input Parameter Value		
Model Input Parameter	*Base*	*Minimum*	*Maximum*
Sub-adult mortality *(yearly %)*	10.9	4.4	44
Adult mortality *(yearly %)*	5	1	10
Initial population size *(individuals)*	250*	50	500
Number of territories available	233	100	1,000
Inbreeding (*number of lethal equivalents*)	0	0	10

The results from the sensitivity testing were exported and analysed in R (R Core Team, 2024). To investigate the relationship between the population growth (λ) and the variables chosen, the Random Forests machine learning regression method was used to identify the most likely predictors of population growth (Cutler et al., 2007). Random Forests (or random decision forests) is a decision-tree modelling technique designed to identify nonlinear associations among multiple correlated predictor variables (Breiman, 2019). Random Forests has been shown to have higher predictive capability compared to alternative statistical techniques (Cutler et al., 2007; Prasad et al., 2006).

Random Forests models were built of 10,000 classification trees, and the relative importance of variables was evaluated based on the percentage variance demonstrated by each of them and by the %IncMSE metric i.e. percentage increase in mean standard error.

Sub-adult Mortality

The multi-factor sensitivity testing and associated analysis suggested that sub-adult mortality has a relatively higher impact on the population viability of the Philippine Eagle. Hence, a more targeted sensitivity analysis was carried out to investigate in further detail how population trends change with the increase of sub-adult mortality only. A hypothetical population with a population growth (λ) of 1 (i.e. stable) was constructed for the purpose of this analysis. This population was set to have an arbitrary initial population size of 250* individuals, with no inbreeding effect, whilst sub-adult and adult mortality were set to 15 % (± 5% EV) and 2.1 (± 1% EV), respectively (these were manually tweaked to obtain a stable population). Each scenario simulation was run 1,000 times and the comparative change in the number of extant individuals at the end of the 100-simulation, deterministic r and gene diversity were all used to evaluate the sensitivity of the population to variation in this parameter.

* Although the initial population size of 250 individuals is meant to be purely theoretical (see *§ Multi-factor sensitivity testing*), it is worth mentioning that this value is very close to the best estimate of Mindanao's carrying capacity based on Species Distribution Models (Sutton et al., 2023)

Senescence

One of the parameters around which there was notable uncertainty was the age at which Philippine Eagles stopped breeding. There was a strong sense by the expert from the Philippine Eagle Foundation that the species is likely to stop breeding at the ege of 25 because this is what has been observed during captive rearing. However, the data is limited and, more importantly, this may be a secondary effect of captive breeding, which doesn't manifest in the wild population. Thus, a dedicated sensitivity analysis was carried out to investigate the potential effects of the presence and length of a post-breeding senescent period.

For this analysis, the same theoretical stable ($\lambda = 1$) population as above (see above *§ Sub-adult Mortality*) was used as a baseline i.e. maximum age of reproduction = 25 years, maximum lifespan = 40 years. Three alternative scenarios, each with an increase of five years in the maximum age of reproduction (i.e. 30, 35, 40) years. Results were compared by looking at the number of individuals at the end of the 100-simulation as well as changes in the number of adult females of breeding age and gene diversity.

Results

Demographic sensitivity analysis

Multi-factor Sensitivity Testing

Overall, the Random Forest model achieved robust performance with a substantial proportion of the variance explained, with minimal residual error (mean of squared residuals = 0.000078, percentage variance explained = 93.66%). The analysis indicated that sub-adult mortality is the best predictor of population growth over 100 years.

The percentage increase in mean squared error (%IncMSE) indicates that sub-adult mortality has the highest importance and contribution to the model's predictive accuracy (Table 6). '%IncMSE' is a direct measure of how much the variable helps reduce the overall prediction error.

Sub-adult mortality also accounted for 92.23% of the total variance in λ, with the next variable in order of explanatory importance (adult mortality) explaining only 4.56% (Table 6).

Table 6. *Contribution of each parameter to the model's predictive accuracy expressed as percentage increase in mean squared error (%IncMSE) and the percentage of variance they explain. Parameters are listed in descending order of % of Variance Explained*

Variable	%IncMSE	% of Variance Explained
Sub-adult mortality (*yearly %)*	0.001824808	92.23
Adult mortality (*yearly %)*	0.00009025113	4.56
Number of territories available	0.00002667176	1.35
Inbreeding (*number of lethal equivalents*)	0.00002344779	1.19
Initial population size (*individuals*)	0.00001342136	0.68

While Random Forest analysis highlights the relative importance of sub-adult mortality in explaining variation in population growth (Figure 3), this does not imply that other variables are unimportant in absolute terms. For instance, initial population size is a factor known to influence the long-term viability of populations, and the model shows how it is likely to affect population growth in some measure (Figure 4). However, among all the variables tested, sub-adult mortality has the greatest impact on the population's ability to grow or decline. A combination of relatively high abundance of individuals in this cohort, as well as the multi-year duration of individuals in that cohort, may explain the results. Moreover, this underscores its critical role in shaping population dynamics, suggesting that changes in this factor, whether positive or negative, would have the most significant consequences for population trajectories (Figure 3a).

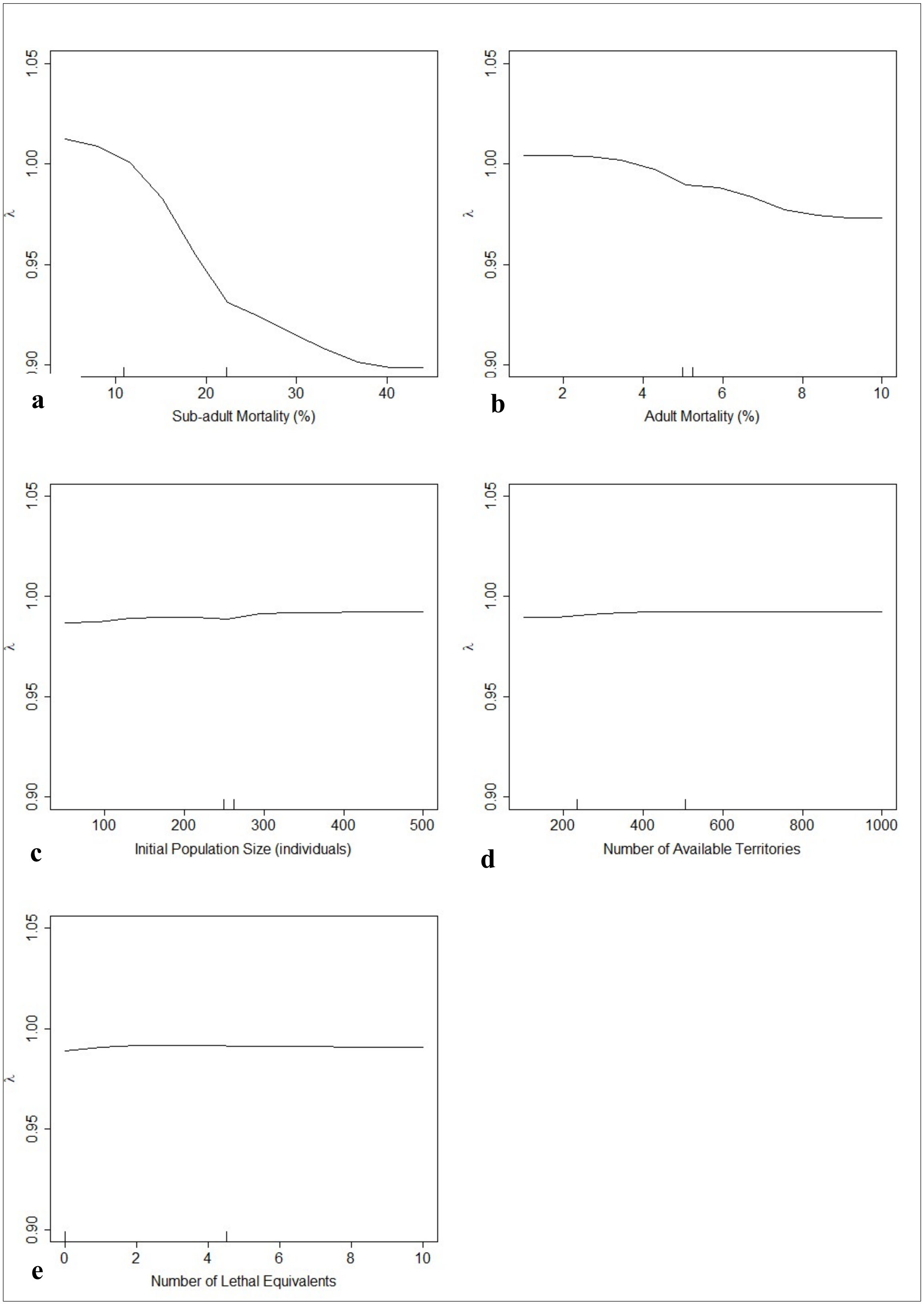

Figure 3. *Relative variation in growth rate due to change in* ***a.*** *% sub-adult mortality,* ***b.*** *% adult mortality,* ***c.*** *initial population size,* ***d.*** *number of available territories, and* ***e.*** *the number of lethal equivalents. The scale of growth rates (on the Y-axis) is standardised to facilitate comparison between graphs.*

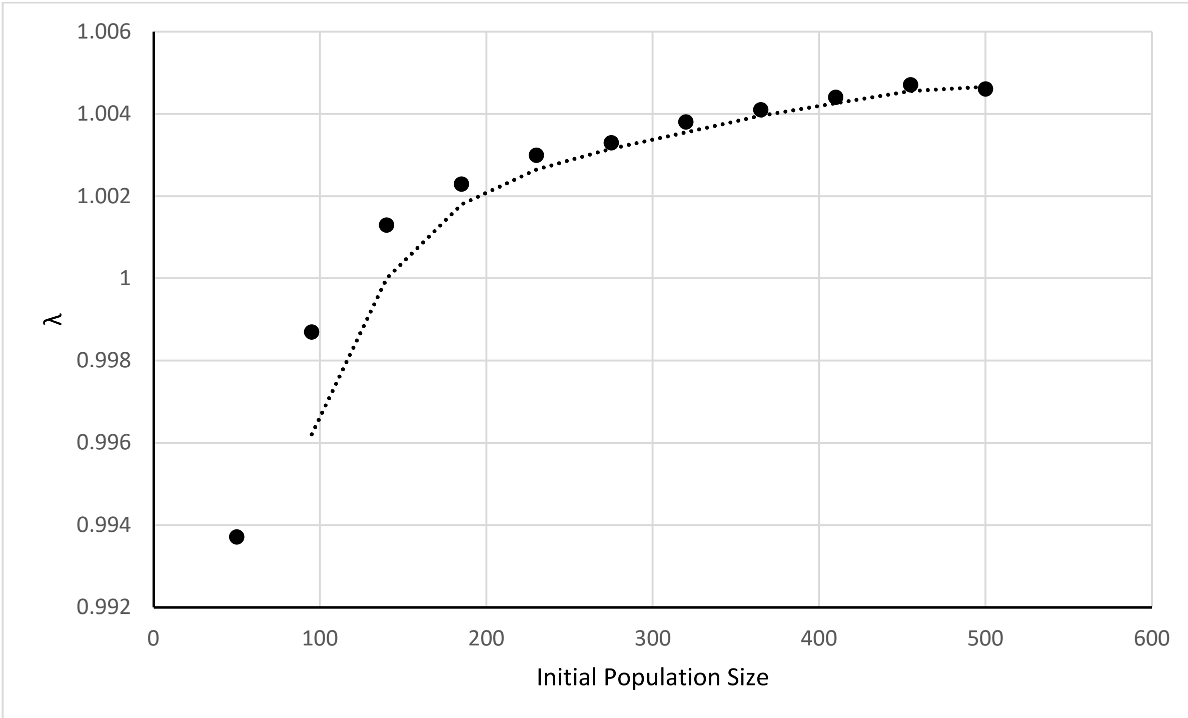

Figure 4. *Variation in growth rate due to changes in the initial population size (number of individuals). The dotted trend line represents the moving average.*

Sub-adult Mortality

The model shows that with the increase in yearly sub-adult mortality, the population is likely to decrease markedly (Figure 5) as a result of a drop in growth rate (Table 7). The mean number of extant individuals at the end of a 100-year simulation period is predicted to decrease from 158 of the baseline model to 110 (-30.3%) with just a 5% increment in sub-adult mortality, to 23 (-85.5%) with a 25% increase (Figure 5) – exhibiting a ~30% decrease every 5% increase in sub-adult mortality.

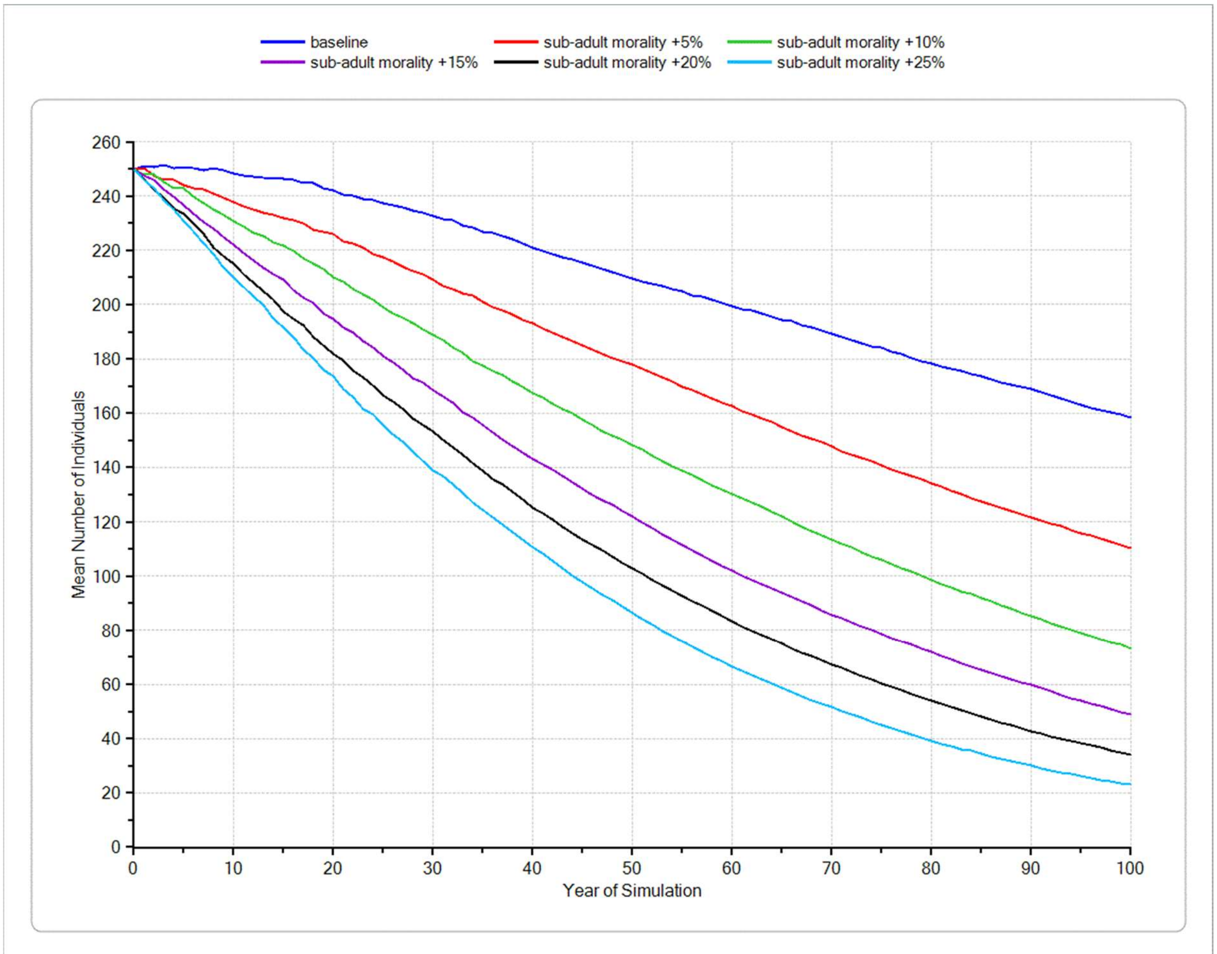

Figure 5. *Variation in the mean number of individuals extant at the end of a 100-year simulation, with a 5%, 10%, 15%, 20% and 25% increase in sub-adult annual mortality starting from a baseline value of 15 % (± 5% EV) – λ =1.*

Table 7. *Changes in growth rate (λ) at the end of a 100-year simulation, with a 5%, 10%, 15%, 20% and 25% increase in sub-adult annual mortality starting from a baseline value of 15 % (± 5% EV).*

Subadult mortality	λ
Baseline	1.001
+5%	0.997
+15%	0.994
+20%	0.990
+25%	0.987

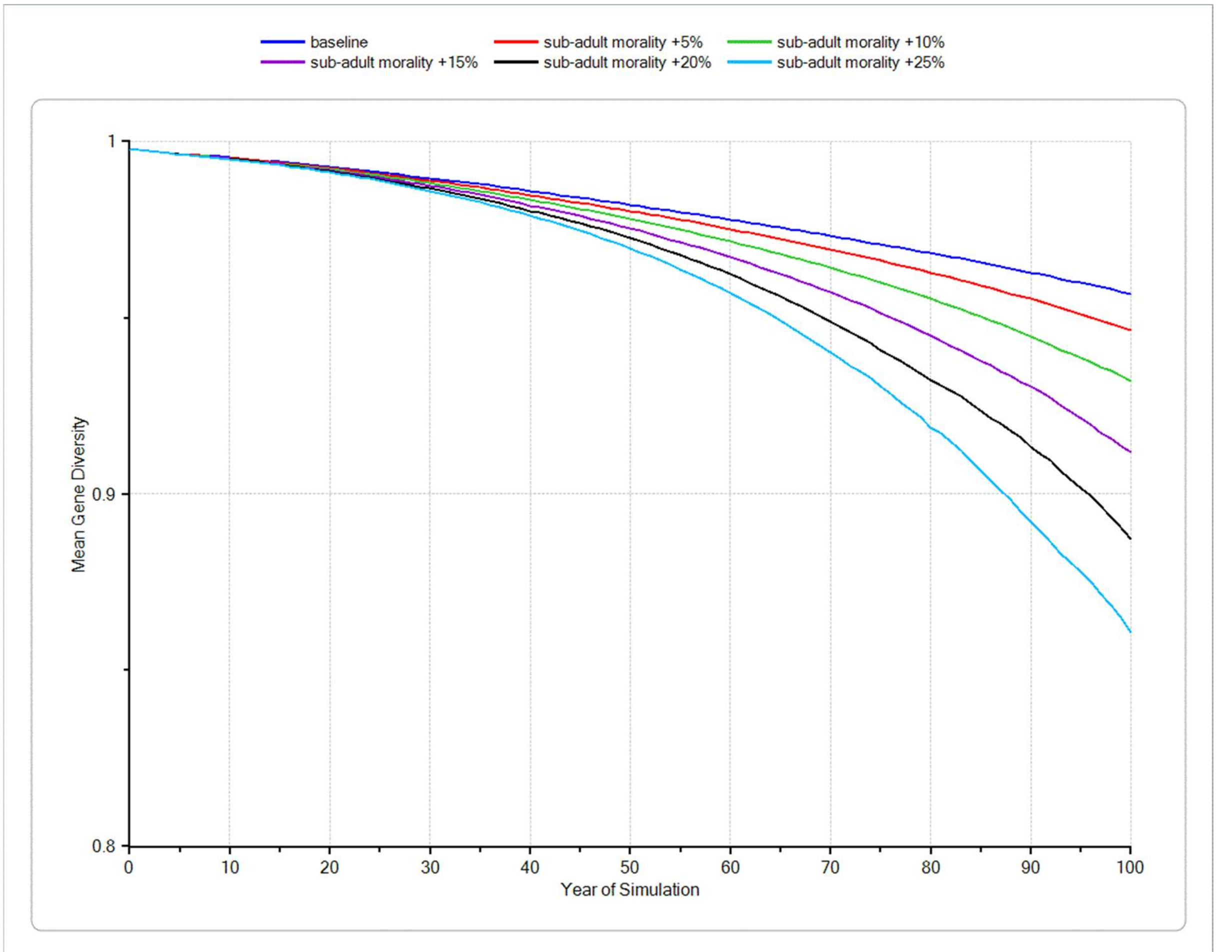

Figure 6. *Change in the mean gene diversity at the end of a 100-year simulation with a 5%, 10%, 15%, 20% and 25% increase in sub-adult annual mortality starting from a baseline value of 15 % (± 5% EV) – λ =1.*

Senescence

Results suggest that the population trend is likely to be significantly affected by the presence and length of a period of post-breeding senescence. The mean number of individuals extant at the end of a 100-year simulation period it is likely to increase by 642% if individuals were able to breed until the expected maximum lifespan, with an increase of 232% if the maximum breeding age were to be just 5 years longer than 25 years currently estimated (Figure 7). In the same simulation, the growth rate is expected to increase by 20.94% in the absence of senescence, with an expected increase of 0.58% with the addition of five breeding years (Table 9).

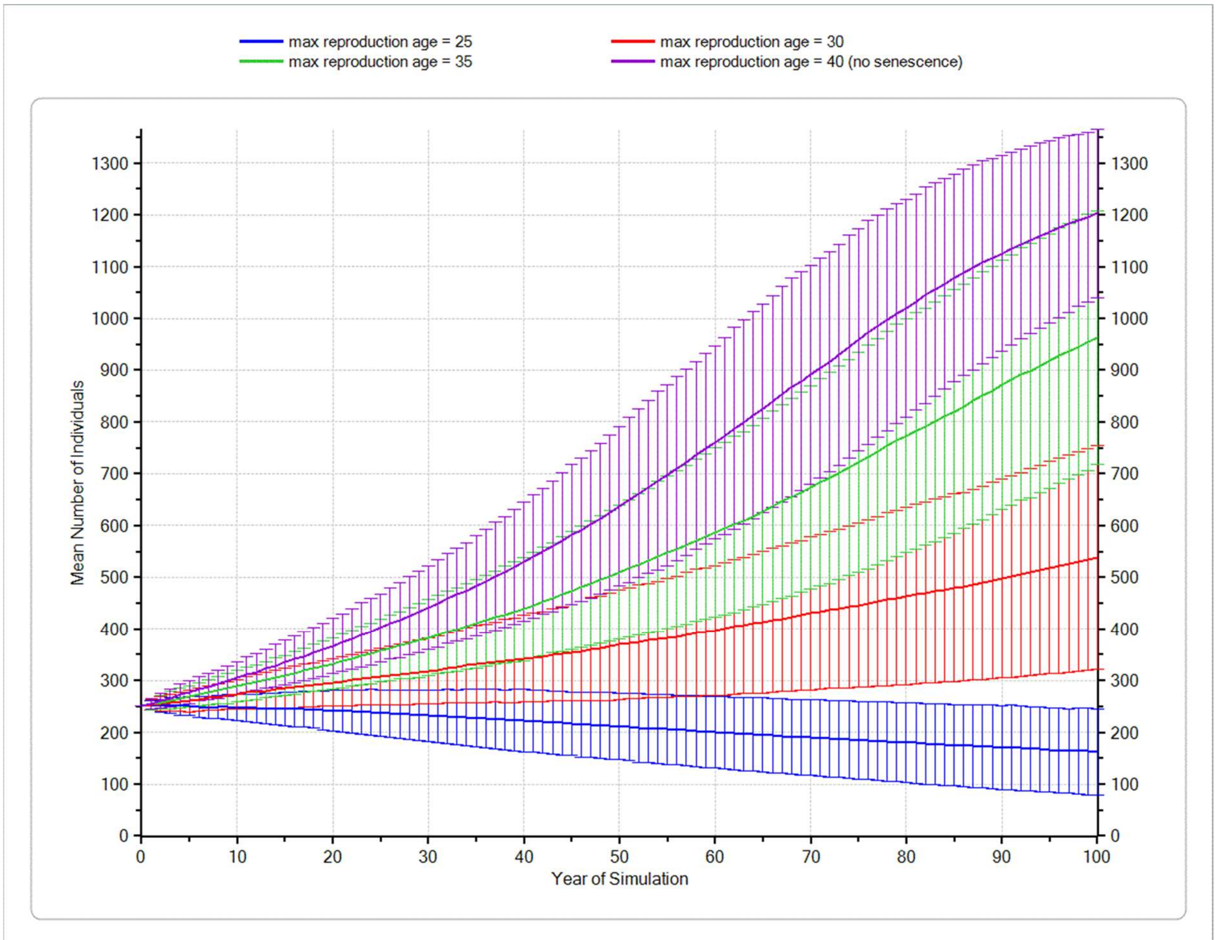

Figure 7. *Change in the mean number of individuals extant at the end of a 100-year simulation, with a maximum breeding age of 25, 30, 35 and 40 (also the maximum lifespan, i.e. no senescence). Error bars represent standard deviation.*

Table 8. *Change in the growth rate (λ) at the end of a 100-year simulation, with a maximum breeding age of 25, 30, 35 and 40 (also the maximum lifespan, i.e. no senescence)*

	λ	**Relative increase**	**Cumulative increase**
Maximum age = 25 years	1.005	-	-
Maximum age = 30 years	1.0109	+0.58%	0.58%
Maximum age = 35 years	1.017	+0.61%	1.20%
Maximum age = 40 years (*no senescence*)	1.23	+20.94%	22.38%

Gene diversity is equally affected by the presence and length of a post-breeding senescence period, with the mean expected heterozygosity expected to increase from 0.96 to 0.99 (i.e. from 15 years senescence to period to the absence of senescence), and the amount of variation around the mean projected values after a 100 years of simulation is also estimated to reduce significantly (Figure 8).

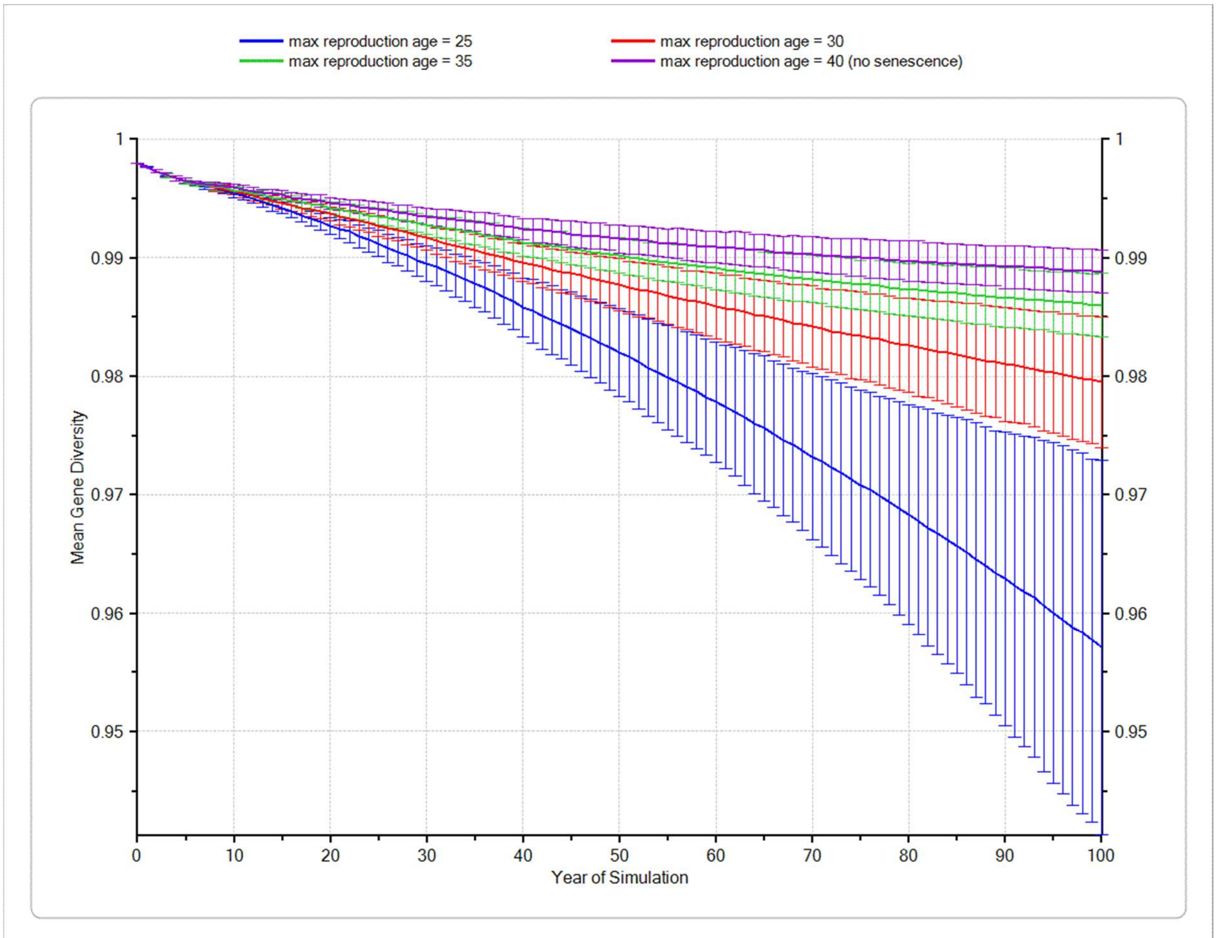

Figure 8. Change in the mean gene diversity at the end of a 100-year simulation, with a maximum breeding age of 25, 30, 35 and 40 (also the maximum lifespan, i.e. no senescence). Error bars represent standard deviation.

Ultimately, the expected presence of a post-breeding senescence of up to 15 years is likely to greatly limit the number of adult females of breeding age, even if the population were to reach reasonably high levels of abundance (Figure 9).

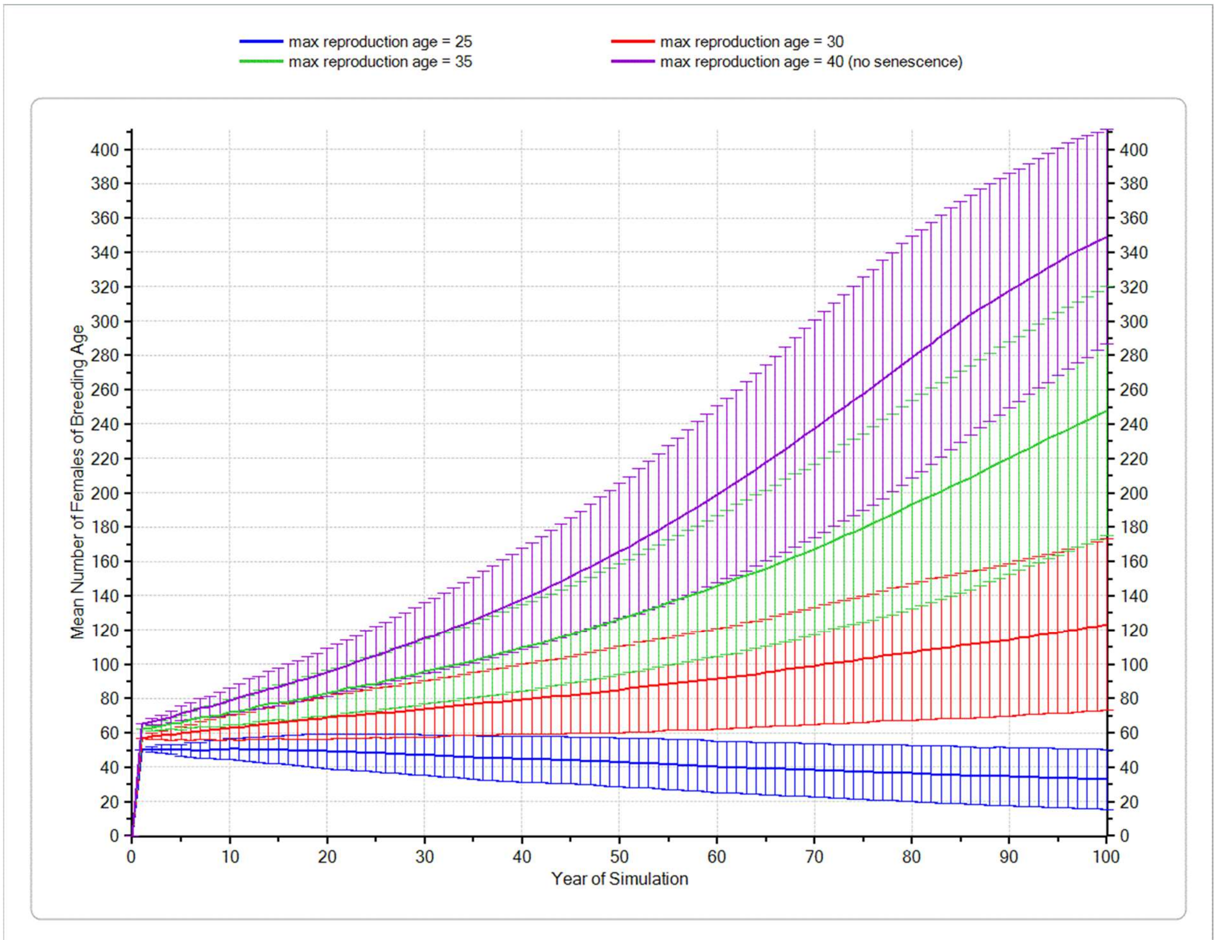

Figure 9. *Change in the number of females of breeding age at the end of a 100-year simulation, with a maximum breeding age of 25, 30, 35 and 40 (also the maximum lifespan, i.e. no senescence). Error bars represent standard deviation.*

Discussion and recommendations

The scope of the population viability analysis reported here reflects the best information currently available on the demography and breeding ecology of the species. Because of this, it was not possible to address all the questions indicated by participants in the first workshop (see *§ Research questions*). Nonetheless, the sensitivity testing provided a framework to infer the importance of the lacking parameters and useful indications to prioritise future research. The sensitivity testing revealed that sub-adult mortality is amongst the most impactful parameters, and this is somewhat supported by information from the Philippine Eagle Foundation on individuals that are brought into their facilities for rescue. Out of 100 eagles that the PEF rescued and admitted since the 1970s, age could the determined with some degree of precision for 59 of them and 50 were between two months and five years of age, i.e. juveniles and sub-adults. Of the 20 Philippine Eagles rescued since 2020, 18 (90 %) were juvenile and immature birds that were either shot, trapped or harmed. This is consistent with the biology of a highly territorial species, in which sub-adults are expected to leave familiar areas in search of their own territories, thereby exposing themselves to greater risks. For this reason, the importance of the amount of available habitat should not be underestimated, as it is likely to be closely linked to the risks sub-adults face during dispersal..

Despite the importance assigned by this analysis to sub-adult mortality, it is crucial to remember that such significance is only comparative, and the population has shown to respond (although less markedly) to other factors such as habitat availability and initial population size. The latter is a particular concern given the isolated nature of the remaining populations.

It would be important for future research investment to be directed to better quantifying some of the parameters here tested, starting with population sizes and trends and with specific attention to real or inferred mortality rates of all classes, but of sub-adults in particular. This would allow for a more precise analysis, which could inform population-specific interventions.

The models have shown that a better understanding of the existence and/or length of a post-breeding senescence period is key to putting the above results into context. Comparatively healthy and large populations may not necessarily ensure long-term viability if individuals have a long period of senescence and the population is characterised by a limited number of breeding individuals. Knowledge on this aspect could be improved by collecting a consistent and sizeable body of evidence on breeding birds currently held in captivity. Data on breeding success or lack thereof should be substantiated by the relevant veterinary tests, which may shed light on the effective causes, e.g. husbandry techniques, biological limitations.

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Appendix I

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Appendix II

Complete list of participants to planning workshop (1st – 4th Sept 2025, Davao City, The Philippines)

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