Modelling population viability of three independent Javan gibbon (*Hylobates moloch*) populations on Java, Indonesia

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Population viability analysis is a predictive procedure that uses a combination of different modelling approaches to estimate species vulnerability to extinction. Javan gibbons (*Hylobates moloch*) are vulnerable to local extinction primarily due to deforestation and hunting for the illegal pet trade. Using the modelling software VORTEX, we assessed the status of Javan gibbons in three areas (Ujung Kulon National Park, Halimun-Salak National Park, and Dieng Mountains) which hold over half of the remaining estimated number of gibbons on Java. Ujung Kulon and Halimun-Salak are long-time protected areas, whereas Dieng Mountains remain unprotected. For each area, we calculated the probability of extinction over a 100-year time period by testing different area-specific scenarios (e.g., hunting, deforestation, and increase in carrying capacity). Our modelling suggests each of the populations has a high chance of becoming extinct within the next 100 years if hunting and deforestation persist. If these threats are eliminated the model shows each of the populations are large enough to persist in the long-term whilst maintaining high levels of current genetic diversity. We conclude that specific actions should be implemented to develop more inclusive conservation management practices, especially improving awareness regarding the illegal wildlife trade and increased protection of wild populations and their habitats.

Key words: PVA; VORTEX; *Hylobates moloch*; illegal pet trade; deforestation; conservation

Introduction

Amongst the tropics, Southeast Asia has one of the highest rates of deforestation, which is undoubtedly the major cause of species decline across the region (Gaveau et al. 2009, 2014). It is estimated that potentially up to half of Southeast Asian mammals could become extinct within the next 100 years (Brook et al. 2003; Sodhi et al. 2010) if current rates of forest loss continue unabated. In addition to forest loss and the fragmentation of remaining forests, hunting also poses a major threat to wildlife the world over, particularly in Southeast Asia where human population density is exceptionally high and wildlife is under constant threat of anthropogenic disturbance and demand for animals and/or their parts (Sodhi et al. 2010; Marshall et al. 2013). These threats are deterministic in nature as they directly increase mortality or decrease fecundity, thereby causing populations to decline (Marshall et al. 2013). If populations are generally large, the risk of extinction is relatively low, but small, isolated populations are at a greater risk of decline due to stochastic processes, and therefore may be more susceptible to local extinctions (Caughley 1994; Cowlishaw and Dunbar 2000).

Population Viability Analysis (hereafter PVA) is a predictive measure used to determine the likelihood of a species' risk of extinction over a pre-defined period of time. The model uses mathematical simulations to estimate extinction probabilities of wildlife populations subject to different deterministic forces and stochastic events (Soule 1985; Stark et al. 2012; Marshall et al. 2013). When paired with empirical data from the field, PVA models can identify several factors that make a species more susceptible to extinction processes and can help to guide conservation management (Sodhi et al. 2010; Marshall et al. 2013).

PVAs have been a widespread tool in species conservation for the past 30 years, helping to provide assessments of species population trajectories and viability (Coulson et al. 2001; Reed et al. 2002); projections of the impacts of potential changes to habitat or direct threats to populations (Coulson et al. 2001; Nilsson 2003); assessments of the relative efficacy of proposed management actions (Nilsson 2003); and predictions for population growth under management practices or habitat limitations (Boyce 1992; Reed et al. 2002; Stark et al. 2012). PVA models are not intended to determine an absolute risk of extinction, rather they are best used to help identify aspects of the system for which more data are needed, help direct funding to priority populations where it can be used efficiently and appropriately (e.g., policy decisions, habitat management, and conservation planning), and overall, to offer insight into which current and potential management /mitigation strategies are likely to have the greatest positive effect on species' long-term survival (Shaffer et al. 2002; Drechsler and Burgman 2004; Stark et al. 2012).

PVAs have been utilised in conservation management for several nonhuman primates (Singleton et al. 2004; Stark et al. 2012; King et al. 2014; Utami-Atmoko et al. 2017), including for different species of gibbons (Tunhikorn et al. 1994; Walker and Molur 2005; Fan et al. 2013; Bryant 2014). In 1994, a PVA (which was a component of the PHVA workshop) (http://www.cbsg.org/pva-process) for Javan gibbons (*Hylobates moloch*) was conducted (Supriatna et al. 1994), and it was concluded there were 386 Javan gibbons left in the wild, surviving only in small, isolated populations, and were at serious risk of going extinct. This conclusion of an extremely small population of Javan gibbons remaining in the wild, led to their Critically Endangered status designation by the IUCN (Andayani et al. 2001; Nijman 2004). The workshop participants concluded that the fundamental threat to the survival of Javan gibbons was low genetic diversity, and with such a small population remaining in the wild, an action plan was set forth to begin immediate active genetic and demographic management. For the small, isolated populations, "rapid habitat expansion, genetic supplementation, translocation, and captive propagation" was to be carried out (Supriatna et al. 1994; Asquith 2001). In contrast, field studies had demonstrated there were potentially large populations of Javan gibbons still living in large tracts of unprotected forests, as well as potentially large, viable populations within the protected area network (Nijman and van Balen 1998; Asquith 2001) not only in western Java, but also in central Java.

Previous assessments of the conservation status for Javan gibbons have concluded that forest loss and the fragmentation of remaining habitat are the primary threats to their survival in the wild (Asquith 2001; Nijman 2004), and it is estimated that less than 10 percent of the original forest remains on Java (Malone et al. 2014). Javan gibbons are found in roughly 30-50 fragmented areas in western and central Java; therefore, protection and management of larger populations of Javan gibbons living in the remaining forest tracts should be a conservation priority (Nijman 2004; Malone 2007). Due to the availability of better information and updated population surveys (Kappeler 1984; Asquith et al. 1995; Nijman 2004) indicating a larger number of gibbons on Java (previous assessments did not include surveys from central Java), and no real consensus on actual population trends and habitat assessment (Asquith 2001; Djanubudiman et al 2004; Nijman 2004; Supriatna et al. 2010), Javan gibbons were reassessed by the IUCN and classified as Endangered in 2006. The change in status from Critically Endangered to Endangered does not suggest that the threats have decreased; in fact, threats continue to increase but not yet to the level necessary to reclassify Javan gibbons as Critically Endangered (IUCN 2017). However, in spite of this updated conservation status and knowledge of larger populations existing in the forests of Java, conservation efforts remain focused primarily on translocation of rescued and rehabilitated Javan gibbons rather than protection of the forest and the remaining wild population (Supriatna 2006).

In our study, we used the most recent survey data from the three largest known populations of Javan gibbons to examine the viability of these populations. The goal of our analysis was to run an updated model with more realistic population parameters, and to examine different management actions based on area-specific scenarios that might be extrapolated to populations throughout western and central Java. We have selected three areas: one that has potential for population increase; one that comprises potentially fragmented populations; and one unprotected forest area that could be subjected to substantial levels of poaching (i.e., hunting for the illegal pet trade). Each population is subject to different conservation issues and pressures; therefore, in the future, creating PVA models for individual forest reserves, national parks, or even the metapopulation, could provide more useful and directed results than an island-wide model, and may assist the authorities in the direction needed to improve species and site management, and guide conservation funding.

Methods

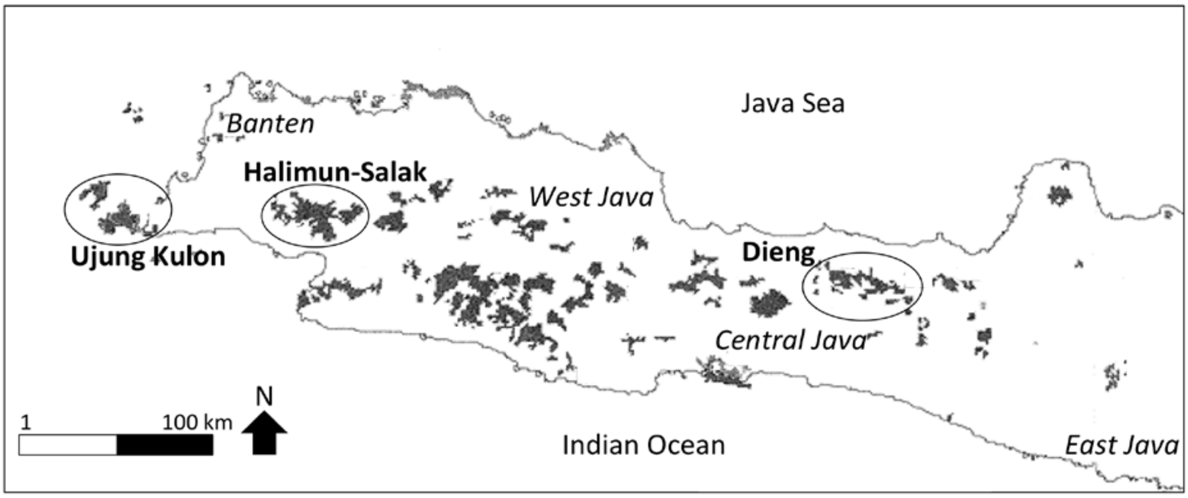
Study species:

Javan gibbons tend to exhibit a socially monogamous mating pattern, living in small social units consisting of an adult pair and their dependent offspring, and typically averaging three to five individuals (Kappeler 1984; Fuentes 2001; Bartlett 2003). The onset of sexual maturity for females is on average eight and a half years, and around age ten for males, with the age at first birth for females usually occurring between age eight and ten (Brockelman et al. 1998). Interbirth interval falls between two to three years (Supriatna et al. 1994; Hodgekiss et al. 2009). Javan gibbons live at average mean densities of approximately 2.5 groups km^2 (Nijman 2006), but this depends on resource abundance (especially the availability of figs), habitat disturbance, and elevation (with higher densities occurring at lower elevations) (Nijman 2006; Kim et al. 2010), and occupy a home range of between 15-37ha (Kim et al. 2010).

Study areas:

We used three sites in our modelling: Ujung Kulon National Park, Halimun-Salak National Park, and Dieng Mountains (Figure 1; Table 1). We chose these sites for the PVA as they represent the three largest known populations of Javan gibbons, including the western and easternmost ones of the species, and each area faces a range of different challenges and opportunities for Javan gibbon conservation.

Figure 1. The island of Java, Indonesia, showing the remaining forest cover including the three study areas: Ujung Kulon National Park, Halimun-Salak National Park, and Dieng Mountains. Province names are indicated in Italics.



<u>Ujung Kulon National Park</u>:

Ujung Kulon (S 6°45', E 105°20') is a UNESCO World Heritage site, located on the southwestern tip of Java, best known for supporting the last remaining population of Javan rhinos (*Rhinoceros sondaicus*). The park comprises a mainland section (Mt. Honje), a peninsula and several islands, mostly covered in lowland forest; Javan gibbons are mostly present in the mainland section with a smaller population on the easternmost part of the peninsula (Tanjung Ranjang). Asquith et al. (1995) (see also: Kappeler 1984; Rinaldi 1999; Djanubudiman et al 2004) present data indicating there are approximately 300 to 560 Javan gibbons living in the park, and it is estimated that only 85 km^2 of the park remains as suitable habitat for them (Nijman 2004).

Halimun-Salak National Park:

Halimun-Salak (S 6°72', E 106°46') has some of the largest remaining contiguous lowland forest on Java; however, small-scale and plantation agriculture, infrastructure development, gold mining, and unsustainable fuel wood and non-timber forest product harvesting threaten the integrity of the area (Nijman 2015). Javan gibbons are present throughout the Halimun area, on Mt. Salak, and in the corridor linking the two (Nijman 2015), but the loss of lowland forest and the presence of enclaves may have led to the population becoming fragmented and thus isolated from one another. Estimates of the number of Javan gibbons in Halimun-Salak vary, but range between 900 and 1,220 individuals (Kool 1992; Asquith et al. 1995; Sugarjito and Sinaga 1999; Nijman 2015), and it is estimated that 400 km^2 of suitable habitat remains for the gibbons (Rinaldi 2003; Djanubudiman et al 2004; Nijman 2004).

Dieng Mountains:

In contrast to Ujung Kulon and Halimun-Salak, the forests of Dieng Mountains (S 7°12', E 109°54'). are entirely unprotected and receive little attention from the conservation community (Nijman and van Balen 1998; Setiawan et al. 2012). The area comprises a mixture of secondary forest and forest plantation dissected by a relatively large number of secondary roads. Javan gibbons are found throughout Dieng Mountains; Setiawan et al. (2012) identified four to five subpopulations with an unknown degree of connectivity between them. It is estimated there are approximately 850 gibbons (Setiawan et al. 2012) living in the Dieng Mountains, and 167 km^2 of forest remains as suitable habitat for them (Nijman 2004; Setiawan et al. 2012).

Table 1: Study site parameters

Area	Location	Status	Elevation (metres above sea level)	Total area	Suitable habitat for gibbons	Estimated population of gibbons
Ujung Kulon	Banten	National Park	0-620	760 km^2	30-85 km^2	300-560
Halimun-Salak	West Java	National Park	500-2,211	1,133 km^2	330-400 km^2	900-1,220
Dieng Mts.	Central Java	Unprotected forest	300-2,565	250 km^2	90-135 km^2	850

Source : Rinaldi (2003); Djanubudiman et al (2004); Nijman (2004); Setiawan et al. (2012).

Definitions and modelling:

We used the software VORTEX V.10 for all analyses (Lacy and Pollak 2014; http://vortex10.org/Vortex10.aspx) to explore the viability of Javan gibbon populations. VORTEX is one of several widely available computer packages that can be used to conduct a PVA. It is a Monte Carlo simulation program that models the effects of deterministic forces as well as demographic, environmental, and genetic stochastic events on wild populations. VORTEX models population dynamics as a set of discrete sequential events that occur according to defined probabilities (Marshall et al., 2013), and is appropriate for modelling Javan gibbon populations as it is designed specifically for mammalian and avian populations with low fecundity and long-life spans (Lacy and Pollak 2014).

We set the simulations to run 500 times over a 100-year period. After each simulation, results recorded were: the probability of extinction (PE), deterministic growth rate (det-r), mean stochastic growth rate (stoc-r), mean number of individuals for surviving populations (N-extant), gene diversity (GD), and the standard deviation (SD) for each. Deterministic-r is the projected growth rate of a population and excludes stochastic events. If stochastic-r is similar in value to det-r, then the population is considered stable, and if stoc-r is less than det-r, the population is considered unstable. When the SD of N is half or more than N, the population is considered to be unstable and thus more susceptible to fluctuation (Stark et al. 2012).

We define a population as the combination of all subpopulations at a particular site (i.e., each site is considered an independent population), and a population was considered extinct when only one sex remained. The baseline model was designed to represent each Javan gibbon population under the conditions for which we understand them to presently exist. Given the life history data on wild Javan gibbons is limited, we selected input values for the demographic variables within the baseline models (Table 2) using available information from the literature (Brockelman et al. 1998; Hodgkiss et al. 2009), parameters used by Supriatna et al. in the 1994 PVA, as well as best estimates for rates of annual hunting (Ujung Kulon: 2 adult females, 2 juveniles; and for both Halimun-Salak and Dieng Mountains: 4 adult females, 4 juveniles). The rate of deforestation for both of the baseline scenarios was set at an estimated 1% annually (Nijman 2004).

We assume the populations of gibbons on Java are at or close to carrying capacity; however, we tested the baseline scenario with two carrying capacities for each site, one low and one high. For the low value, we set the carrying capacity equal to the initial population size, and for the high value, we divided the total estimated habitat available for Javan gibbons in each area by the average exclusive territory range of one group, and then multiplied that by the average group size (Fan et al. 2013).

Currently, there is no data on inbreeding depression on Javan gibbons in the wild; however, we tested the effect of inbreeding for sensitivity purposes (3.14; 50% due to lethal alleles) in both baseline scenarios. It has been suggested that with relatively large population sizes, as used in our models, inbreeding depression will most likely have very little effect on the final outcome of the model (Nilsson 2003; R. Lacy in litt. 2016).

We did not model catastrophes in our PVA as there is not any available information on the probable impact of disease on wild populations of Javan gibbons, nor of the possible effect of small scale forest fires on the island. In absence of this data, any decrease of habitat, whether caused by agricultural expansion or small-scale fire, is accounted for in an annual decrease in carrying capacity. Furthermore, to test sensitivity of mortality rates, we subjected the three different populations to increased rates for both infant and dispersing gibbons (age groups 0-1 and 7-8 years; mortality rate 15 ± 4%).

Table 2. Species-specific parameters: Input values and rationale for values used in the baseline scenario(s) EV: environmental variance; SD: standard deviation; PVA: population viability analysis.

Species-specific parameters	**Input Value**	**Rationale**
Inbreeding depression	0.0	Inbreeding is unlikely to have a significant effect on populations of modelled sizes (all three populations > 100) (Robert Lacy, in Litt; Supriatna et al. 1994).
EV correlation between reproduction and survival	1	Good survival years tend to be good years for reproduction.
EV correlation among populations	0	Populations are considered to be independent of one another.

Dispersal age range for females and males/survival rate at dispersal	5-8; 50%	Gibbons tend to disperse at the sub-adult age or upon sexual maturity (Supriatna et al. 1994; Brockelman and Reichard 1998).
Breeding system	Long-term monogamy	Gibbons tend to exhibit long-term pair bond associations (Supriatna et al. 1994; Brockelman and Reichard 1998).
Age of first reproduction (yr.) for: females/males	8 female: 10 male	Age of first reproduction tends to be between 8 and 10 for both males and females in wild populations of gibbons (Brockelman and Reichard 1998; Supriatna et al 1994; Tunhikorn et al 1994).
Percent adult females breeding	33 ± 17	The proportion of females breeding each year determines the interbirth interval. This interval is reported to be three years in the wild meaning 67% of adult females on average do not produce offspring (Brockelman and Reichard 1998; Supriatna et al. 1994).
Maximum number of broods per year	1	Female gibbons typically give birth to only one baby per year (Husbandry Manual for Javan Gibbons 2008).
Maximum number of progeny per brood	1	Female gibbons typically give birth to only one baby as twins are rare (Husbandry Manual for Javan Gibbons 2008).
Max age of reproduction (yr) also equals maximum lifespan	25	Gibbons are assumed to be able to reproduce their entire adult life. The estimated maximum age of 25 is based on several studies done on captive gibbons (Supriatna et al 1994; Hodgkiss et al 2009).
Sex ratio at birth (% males)	50	There is not any data on sex ratio for wild gibbons (Supriatna et al 1994).
Mortality rates for all ages, female and males	10 ± 3 for age 0-1/7-8; 5 ± 1 for every other age class	Mortality rates are equivalent to those used in the 1994 PVA (Supriatna et al 1994) for both females and males for all scenarios.

Area-specific scenarios:

In our model, we assume all three populations to be independent of one another and subject to similar environmental factors, albeit at potentially different rates of intensity as indicated in the scenarios. We included rates of deforestation and hunting (i.e., removal of gibbons for the illegal pet trade) as those parameters that can be influenced by management practices or a change in human behaviour, and specific to each area. Without definitive data indicating how many Javan gibbons are removed from the forest annually for the illegal pet trade, all estimates of hunting (modelled as *Harvest* in Vortex) are purely arbitrary. We modelled habitat loss as an annual percentage decrease in carrying capacity (=K*(proportion of previous year's forest cover remaining ^ year)), and the percentage is based on estimated rates of annual forest loss in each area (Nijman 2004). Importantly, the different scenarios modelled allow us to predict the probable outcome of failing to implement any conservation management actions in each of the designated areas in the immediate future.

Results

Baseline scenarios:

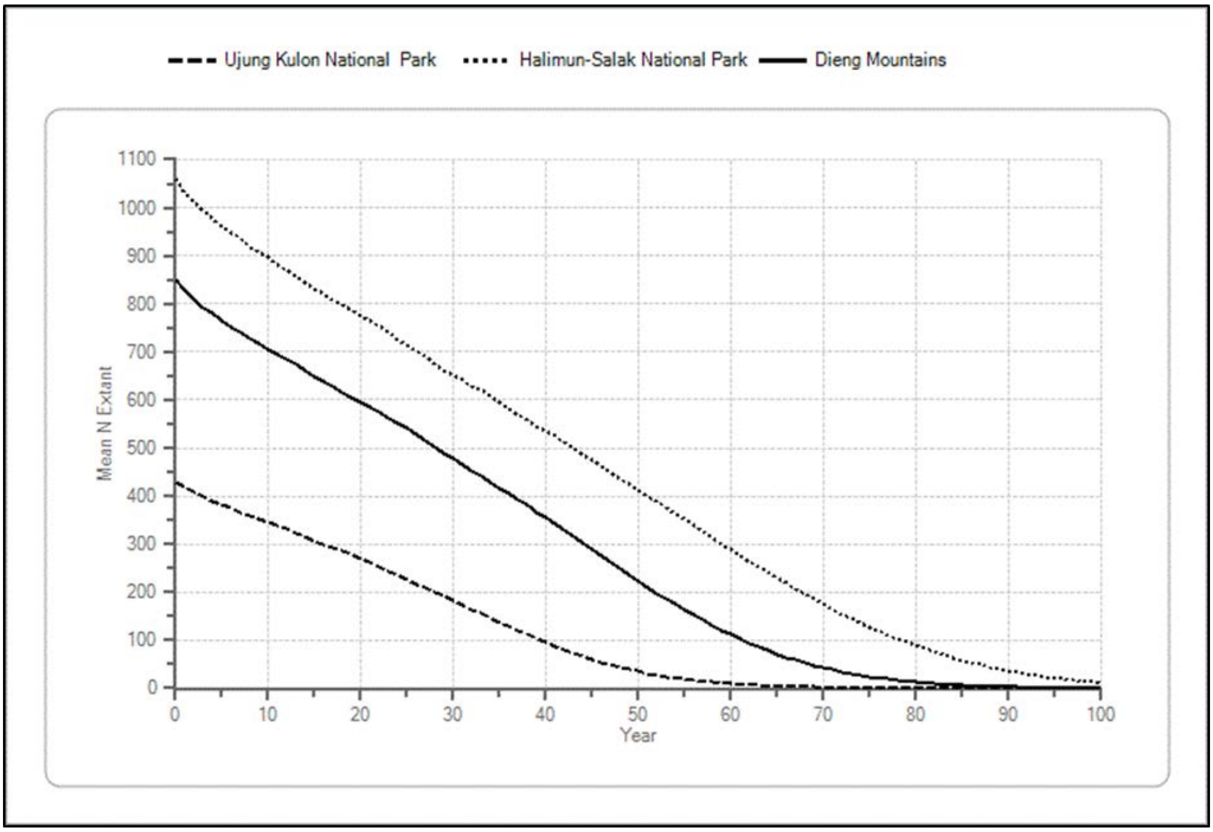
Our baseline modelling, which incorporated 1% annual deforestation and fairly low levels of hunting, predicted a declining population trend for Javan gibbons in each of the three study sites (Table 3; Figure 2), with high probabilities of extinction within 100 years in Ujung Kulon (97 and 100% probability for the high and low carrying capacity scenarios respectively), Halimun-Salak (44 and 92%), and Dieng Mountains (85 and 100%). The deterministic population growth rate was 0.011 and the mean stochastic population growth rate ranged from -0.052 to -0.018 for the three populations in both baseline scenarios.

Table 3. Results from the baseline scenarios (500 iterations over 100 years) for three independent Javan gibbon populations on Java. Initial N: initial population size (for Ujung Kulon and Halimun-Salak the average between the low and high population estimate was used for analysis); Carrying Capacity (N=K) and increased carrying capacity; Stoc-r: mean growth rate (mean stochastic population growth/decline rate); N-extant: mean number of individuals not extinct after 100 yr.; GD: genetic diversity or the mean 'expected heterozygosity' remaining in the extant populations; SD: standard deviation; Det-r for all three populations: 0.011.

Site & Scenario	PE (%)	Stoc-r ± SD	N-extant ± SD	GD ± SD (%)
Ujung Kulon (initial N=430)				
Low K (=430)	100	-0.052 ± 0.072	0 ± 0	0 ± 0
High K (=817)	97.8	-0.046 ± 0.072	99 ± 68	97.8 ± 0.7
No hunting or deforestation (low K)	0	0.009 ± 0.054	387 ± 49	98.5 ± 0.2
No hunting or deforestation (high K)	0	0.008 ± 0.053	424 ± 55	98.6 ± 0.2
Deforestation only (low K)	0	0.008 ± 0.055	148 ± 12	97.5 ± 0.3
Hunting only (low K)	46.8	-0.029 ± 0.086	164 ± 116	96.8 ± 3.3
Halimun-Salak (initial N=1060)				
Low K (=1060)	92.2	-0.036 ± 0.068	108 ± 77	98.4 ± 0.5
High K (=3846)	44.4	-0.018 ± 0.061	732 ± 458	99.3 ± 0.3
No hunting or deforestation (low K)	0	0.009 ± 0.053	966 ± 104	99.4 ± 0.1
No hunting or deforestation (high K)	0	0.009 ± 0.052	2717 ± 844	99.6 ± 0.1
Deforestation only (low K)	0	0.009 ± 0.053	372 ± 21	99.0 ± 0.1
Hunting only (low K)	0.4	0.001 ± 0.054	786 ± 235	99.3 ± 0.3
Fragmented population	37.8	-0.029 ± 0.054	87 ± 50	97.0 ± 1.0
Fragmented population, no hunting or deforestation	0	0.009 ± 0.032	1008 ± 79	99.4 ± 0.0
Dieng Mountains (initial N=850)				

Low K (=850)	100	-0.043 ± 0.070	0 ± 0	0 ± 0
High K (=1298)	84.8	-0.036 ± 0.068	176 ± 98	98.7 ± 0.3
No hunting or deforestation (low K)	0	0.009 ± 0.053	792 ± 82	99.3 ± 0.1
No hunting or deforestation (high K)	0	0.009 ± 0.053	1172 ± 147	99.5 ± 0.1
Deforestation only (low K)	0	0.009 ± 0.054	301 ± 21	98.7 ± 0.1
Hunting only (low K)	26.4	-0.015 ± 0.060	396 ± 246	98.9 ± 0.5

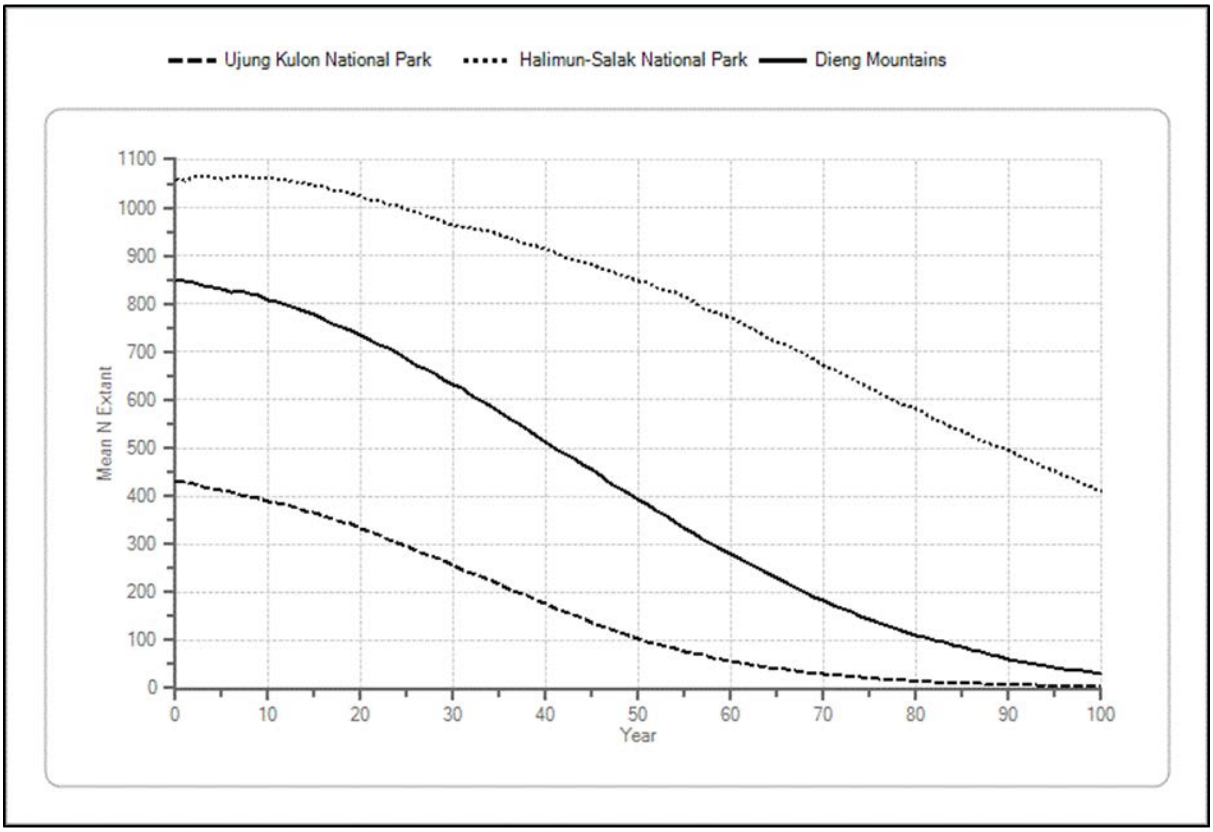
Figure 2: Baseline scenario run for 500 iterations representing 100 years showing the mean number of extant individuals for the three independent populations. *Deforestation*: -1.0% annually; *Hunting*: Ujung Kulon: 2 infants/2 adult females; Halimun-Salak: 4 infants/4 adult females; Dieng Mts.: 4 infants/4 adult females. **Low K** (carrying capacity is equal to initial population size).



Increasing the carrying capacity in each population within the baseline scenario reduces the probability of extinction over the next 100 years; however, there remains almost a 98% chance of extinction in Ujung Kulon and an 85% chance in Dieng Mountains (Figure 3). The population in Halimun-Salak remains relatively more stable with a 44% chance of becoming extinct in the next 100 years (Table 3).

Figure 3: Baseline scenario run for 500 iterations representing 100 years showing the mean number of extant individuals for the three independent populations. *Deforestation*: -1.0%

annually; *Hunting*: Ujung Kulon: 2 infants/2 adult females; Halimun-Salak: 4 infants/4 adult females; Dieng Mts.: 4 infants/4 adult females. **High K**



Sensitivity testing:

Our sensitivity testing of the impacts of inbreeding and of higher mortality rates for infant and dispersing gibbons on the baseline model showed that inbreeding had no impact on the model results, but that higher mortality rates had major impacts, reducing stochastic-r and increasing the probability of extinction (Table 4).

*Table 4***.** Results from baseline scenarios testing the effect of inbreeding depression 3.14: 50% lethal equivalents) and high rates of mortality (age groups 0-1 up to 7-8 years: 15 ± 4%) on each individual population. Stoc-r: mean growth rate (mean stochastic population growth/decline rate); SD: standard deviation; Det-r for all three populations: 0.011.

	PE (%)			**Stoc-r (SD)**		
	Baseline	**Inbreeding**	**High mortality**	**Baseline**	**Inbreeding**	**High mortality**
Ujung Kulon						
Low K	100	100	100	-0.052 ± 0.072	-0.054 ± 0.073	-0.066 ± 0.075
High K	97.8	98.8	100	-0.046 ± 0.072	-0.047 ± 0.072	-0.064 ± 0.075

Halimun-Salak						
Low K	92.2	93.8	100	-0.036 ± 0.068	-0.036 ± 0.068	-0.050 ± 0.072
High K	44.4	41.6	95.0	-0.018 ± 0.061	-0.019 ± 0.063	-0.046 ± 0.071
Dieng Mountains						
Low K	100	100	100	-0.043 ± 0.070	-0.043 ± 0.070	-0.058 ± 0.073
High K	84.8	85.4	100	-0.036 ± 0.068	-0.036 ± 0.068	-0.054 ± 0.073

Area-specific scenarios:

The results from our model show that if any of the populations of Javan gibbons living in Ujung Kulon, Halimun-Salak, and Dieng Mountains are not subjected to hunting or deforestation, they will remain stable and are likely to persist for the next 100 years (Table 3). This demonstrates the importance of initiating site-specific conservation programs, as each population is sensitive to varying levels of threats (i.e., rates of hunting and/or deforestation).

If the level of hunting is occurring at the simulated rate in the model, the population of Javan gibbons living in Ujung Kulon will become extinct in the next 100 years (refer to Table 5). The rate of extinction will be exacerbated and inevitable if there is a persistent rate of deforestation, with the population of Javan gibbons going extinct in the next 45 years. Modest rates of deforestation, in the order of 1.2% annually over the 100-year period, leads to a decline in the population with only 135 individuals surviving.

If the population of Javan gibbons living in Halimun-Salak is fragmented, consisting of smaller subpopulations such as we modelled, and the rates of hunting and deforestation are persistent for the next 100 years, each subpopulation will suffer a drastic decline, with the three smallest subpopulations going extinct within the next 100 years (refer to Table 5). One of the subpopulations (N = 25) will become extinct within 10 years, and is significantly unstable with a stoc-r value of -0.156. The population as a whole (N = 1,060) suffers a gradual decline decreasing to a final population of just 86 individuals in 100 years. However, if deforestation and hunting are eliminated, the population has a high probability of survival even if it is fragmented.

We modelled two different scenarios with varying levels of hunting in Dieng Mountains. In the scenarios where only hunting is modelled, the population suffers a steady decline, and when more individuals are removed from the population annually, it will become extinct within 46 years (Table 5). When hunting is coupled with a relatively low, but constant rate of deforestation (1.2% per year), the population will inevitably become extinct within 45 years, if rates of hunting remain high.

Table 5: Results from area-specific scenarios for Ujung Kulon National Park, Halimun-Salak National Park, and Dieng Mountains. PE: probability of extinction; Stoc-r: mean growth rate (mean stochastic population growth/decline rate); N-extant: mean number of individuals which are not extinct after 100 yr.; GD: genetic diversity or the mean 'expected heterozygosity' remaining in the extant populations; SD: standard deviation. Det-r for all three populations: 0.011.

Site & Scenario	**PE (%)**	**Stoc-r ± SD**	**N-extant ± SD**	**GD ± SD (%)**
Ujung Kulon: Higher carrying capacity (K=473)				
No hunting or deforestation	0	0.008 ± 0.053	424 ± 55	98.6 ± 0.2
Deforestation (1.2%)	0	0.007 ± 0.056	135 ± 10	97.4 ± 0.3
Hunting (6 adults (4F 2M/6 infants)	100	-0.070 ± 0.094	0 ± 0	0 ± 0
Deforestation and hunting	100	-0.073 ± 0.098	0 ± 0	0 ± 0
Halimun-Salak: Fragmented populations				
Subpopulation 1 (N=25)	100	-0.157 ± 0.087	0 ± 0	0 ± 0
Subpopulation 2 (N=500)	39.0	-0.020 ± 0.064	86 ± 49	97.0 ± 1.0
Subpopulation 3 (N=145)	100	-0.067 ± 0.080	0 ± 0	0 ± 0
Subpopulation 4 (N=315)	96.8	-0.040 ± 0.073	27 ± 14	94.9 ± 1.6
Subpopulation 5 (N=75)	100	-0.092 ± 0.076	0 ± 0	0 ± 0
Metapopulation (N=1,060)	37.8	-0.029 ± 0.054	87 ± 50	97.0 ± 1.0
No hunting or deforestation				
Subpopulation 1 (N=25)	49.4	-0.012 ± 0.109	12 ± 7	64.9 ± 17.8
Subpopulation 2 (N=500)	0	0.009 ± 0.054	449 ± 55	98.7 ± 0.1%
Subpopulation 3 (N=145)	0	0.006 ± 0.058	119 ± 24	95.3 ± 1.0%
Subpopulation 4 (N=315)	0	0.008 ± 0.055	282 ± 36	98.0 ± 0.3%
Subpopulation 5 (N=75)	0.40	0.002 ± 0.067	53 ± 17	90.1 ± 4.0%
Metapopulation (N=1,060)	0	0.008 ± 0.032	909 ± 74	99.4 ± 0.1%
Dieng Mountains: High levels of hunting (N=850; K=935)				
Hunting (6 adults/6 infants = 12)	43.4	-0.024 ± 0.071	390 ± 263	98.8 ± 0.7%
Hunting (12 adults/12 infants = 24)	100	-0.070 ± 0.092	0 ± 0	0 ± 0
Deforestation (1.2%) and no hunting	0	0.009 ± 0.053	269 ± 15	98.7 ± 0.1%
Deforestation and hunting (1.2% and 12 ind.)	83.2	-0.040 ± 0.082	72 ± 55	97.2 ± 1.5%
Deforestation and hunting (1.2% and 24 ind.)	100	-0.073 ± 0.094	0 ± 0	0 ± 0

*Carrying capacity (K) for Halimun-Salak and Dieng Mountains 10% increase in N.

Discussion

PVA models have become a common tool in conservation science by providing the necessary framework for establishing management policies and guidelines for protecting threatened species and their habitats (Reed et al. 2002); however, it must be acknowledged the results of a PVA are only as accurate as the data on which they are based (Coulson et al.

2001; Marshall et al 2013). The current ecological and population data available on Javan gibbons is limited or inconsistent; therefore, we relied on the most recent population and demographic data available, as well as using the 1994 Javan Gibbon PVA as a guide for our model (Supriatna et al. 1994; Asquith et al. 1995; Nijman 2004).

If the current situation on Java remains unchanged (i.e., rates of deforestation and hunting remain relatively low and do not increase in the future), and if the current population estimates for the modelled populations are indeed accurate, there is time to enact serious conservation management schemes to ensure extinction does not occur within the next century. Populations of Javan gibbons may respond differently to various management scenarios; therefore, it is crucial to develop conservation strategies that are based on the characteristics and trends of individual populations and their habitat.

Area specific scenarios:

Ujung Kulon National Park:

Due to the presence of Javan rhinos on the peninsula, active protection of Ujung Kulon is above average when compared to other protected areas on Java. Considering the higher level of protection in the park, and its remote location far removed from any urban centres, the poaching of Javan gibbons is assumed to be low, however, there is not available data to substantiate this. While forest loss on the peninsula is negligible, the lower parts of Mt. Honje are subject to small-scale logging (Whitten et al. 1996; V. Nijman pers. obs.). Primary forest remains on Mt. Payung in the west of the park, and currently there are no Javan gibbons living there, thus potentially making it an ideal area for future population increase (either through natural dispersal or translocation) (Kappeler 1984). Therefore, if the high level of protection and relative inaccessibility is maintained in Ujung Kulon, and if Javan gibbons manage to disperse to Mt. Payung or if this area is used as a future translocation site thereby increasing the habitat, then the population of Javan gibbons in Ujung Kulon will have a high probability of surviving without human intervention.

Halimun-Salak National Park:

Halimun-Salak is relatively well-managed, however, the park remains under pressure from human encroachment and low levels of deforestation (Nijman 2015). Indigenous Kasepuhan and Baduy people live on the southern and northern borders of the park and depend heavily on its natural resources (Whitten et al. 1996). In addition, the park (along with the better-known neighbour, Gunung Gede-Pangrango National Park) is an important watershed for western Java, including the major urban conglomerates such as Jakarta, Bogor, Tangerang, and Bekasi. Within the park there are several large enclaves including plantations, villages, and the Nirmala tea plantation which spans approximately 10 km2 (1,000 ha) (Kim et el. 2010; Nijman 2015). High mountains and plantations throughout the park may potentially result in a higher degree of fragmentation with varying levels of connectivity between forest patches; therefore, Javan gibbons living in the park may reside in isolated populations and each population may need to be managed differently, or at least conservation management should include corridors allowing Javan gibbons to disperse efficiently between forest patches (if possible).

Dieng Mountains:

Numerous communities of people live inside and adjacent to the forests, all relying to some degree on it for their livelihood, thus inevitably placing continuous pressure on natural resources in the area. In addition, Dieng Mountains are situated near, and are well-connected to, the large urban centres along Java's north coast. The forests surrounding Dieng Mountains are largely unprotected leaving the populations of Javan gibbons living in these areas potentially at greater risk of being hunted for the illegal pet trade. Therefore, we expect levels of hunting to be higher than in Ujung Kulon and Halimun-Salak National Parks. Furthermore, considering the area is unprotected, the forest is more at more risk for fire due to small-scale clearing of land for agriculture. These threats need to be addressed and considered when devising an action plan for Javan gibbon conservation.

Conservation measures

Fortunately, rates of deforestation on Java (in general) have slowed in recent years, though small-scale land clearing still poses a threat to both protected and unprotected areas where Javan gibbons are still found (Nijman 2004), and the expanding human population will continue to put pressure on the forests across the island. Deforestation may have a significant impact on the population size, particularly if populations already exist at carrying capacity. Fan et al. (2013) found carrying capacity to be the limiting factor for the Cao-vit gibbon *(Nomascus nasutus*) in their PVA model, and concluded the current population would reach its limit within the next 40 years. According to our PVA, the three Javan gibbon populations are likely to go extinct if hunting and deforestation rates continue at the modelled rate. However, all three populations are still large enough to persist and maintain high genetic diversity over the next 100 years if deforestation and hunting can be minimised.

If Javan gibbons exist in populations of fewer than ~100 individuals, such as those modelled in the fragmented population scenarios for Halimun-Salak (N = 25;75), they are more sensitive to increased levels of annual hunting and persistent rates of deforestation, as well as higher rates of mortality and loss of genetic diversity, and thus are at a great risk of extinction. Therefore, smaller populations would benefit from increased protection, as well as potential periodic genetic supplementation via translocation. The Hainan gibbon (*Nomascus hainanus*) is considered to be one of the rarest mammals living today, yet has persisted for over 30 years at a relatively low population size consisting of approximately 25 individuals without human intervention (Bryant et al. 2016). Subpopulations of up to at least 500 Javan gibbons residing in habitat capable of sustaining larger populations, would benefit from increased protection and could potentially expand in numbers by natural reproduction with potentially no need of supplementation from other sources (i.e., translocation). By implementing various management strategies to decrease hunting and deforestation (such as more stringent forest patrol by rangers and an increase in local awareness regarding the protected status of Javan gibbons and the illegality of keeping primates as pets), the declining population trend could possibly be slowed, perhaps reversed, and the population could become more stable through the years. All populations of Javan gibbons would benefit from constant and persistent monitoring and increased habitat protection.

Our model illustrates that the threat of hunting for the illegal pet trade should not be underestimated and should be regularly monitored and assessed. The number of Javan gibbons openly offered for sale in the wildlife markets in Java has declined significantly over the last 25 years (Nijman et al. 2015), and while in the past Javan gibbons were ubiquitously present in the markets, currently they are very rarely seen (V. Nijman pers. obs.). Whether or not this means the number of Javan gibbons extracted from the wild has declined at a similar rate is unknown, as we still see a relatively high number of individuals, particularly infants, coming into rescue centres (Jaima S; Vincent N pers. obs.) seemingly from online illegal wildlife trade sources (with traders openly selling infant Javan gibbons on Facebook and Instagram, for example). There is evidence that gibbons are being traded online via different social media platforms (TRAFFIC 2016), so it would seem the illegal trade network is shifting from open markets to online forums, and is unfortunately more difficult to monitor and more difficult to enforce regulations. Therefore, it is crucial to engage with moderators of social media platforms to help put an end to the trafficking of wildlife via online sources.

Conclusion

Our VORTEX modelling analysis will hopefully provide incentive to move forward in conservation efforts for Javan gibbons by highlighting the immediate threats, and developing management plans and strategies which seek to preserve the wild populations and their habitats. In addition, it would prove beneficial to conduct PVAs more regularly in order to assess current population trends and ensure management strategies are implemented that remain relevant to specific populations and areas of western and central Java where Javan gibbons still remain.

In light of our findings and more recent survey data collected over the past two decades, it may be necessary to revisit and reassess the current management strategies for Javan gibbon conservation (cf. Asquith 2001). Our modelling highlights the fact that large, viable populations of Javan gibbons still persist on Java, and that these populations require protection from deforestation, fragmentation of remaining forest, and hunting to survive in the long-term. Despite the widespread belief that the island of Java is completely deforested, significant forest areas do still remain intact, and should receive higher protection, thus benefiting a diverse range of endemic flora and fauna (Nijman 2004). Additionally, a large proportion of the Javan gibbon population has survived outside of the protected area network in poorly protected forests in central Java; one of the greatest contributions to the survival of Javan gibbons, and should be a conservation priority, would be to increase protection of the forests in central Java.

Given that our model illustrates that hunting is a major threat to the viability and survival of even the largest gibbon populations on Java, increased collaboration between social media networks, wildlife agencies/rescue centres, and law enforcement agencies should be a priority in order to improve detection of illegal trade on social media platforms, and to ensure that prolific dealers in the trade network are targeted in a coordinated and effective manner. The wide-scale monitoring of illegal activity on social media sites is relatively absent and remains a challenge for conservationists and law enforcement agencies.

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