

Modelling Population Viability of Three Independent Javan Gibbon (*Hylobates moloch*) Populations on Java, Indonesia

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Keywords

Population viability analysis · Population modelling · *Hylobates moloch* · Illegal pet trade · Habitat loss · Conservation

Abstract

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 loss of habitat and hunting for the illegal pet trade. Using the modelling software VORTEX, we assessed the status of Javan gibbons in 3 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.

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Introduction

Amongst the tropics, South-East 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 South-East 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 South-East 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., 2009]. 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; Cowlshaw 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 predefined 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., 2009]. 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 and funding [Sodhi et al., 2010; Marshall et al., 2013].

PVA has 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 utilized in conservation management for several non-human primates [Singleton et al., 2004; Stark et al., 2012; King et al., 2014; Utami-Atmoko et al., 2017], including 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 Population and Habitat Viability Assessment workshop) (<http://www.cpsg.org/pva-process>) for Javan gibbons (*Hylobates moloch*) was conducted [Supriatna et al., 1994], and it was concluded that there were 386 Javan gibbons left in the wild, surviving only in small, isolated populations, and that they 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 designated 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” were 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 of 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% 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 [Andayani et al., 2008]. 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 3 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 selected 3 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 help the authorities to improve species and site management, and guide conservation funding.

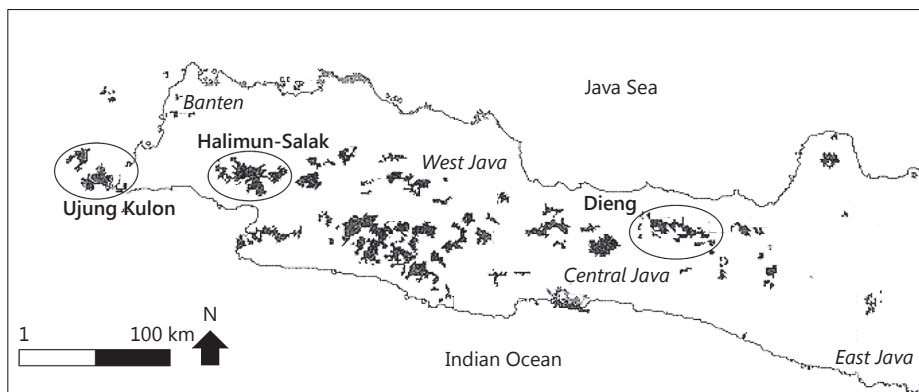


Fig. 1. The island of Java, Indonesia, showing the remaining forest cover including the 3 study areas: Ujung Kulon National Park, Halimun-Salak National Park, and Dieng Mountains. Province names are indicated in italics.

Methods

Study Species

Javan gibbons tend to exhibit a socially monogamous mating pattern, and live in small social units consisting of an adult pair and their dependent offspring, typically averaging 3–5 individuals [Kappeler, 1984; Fuentes, 2000; Bartlett, 2003]. The onset of sexual maturity for females is on average 8.5 years, and around age 10 for males, with the first birth for females usually occurring between age 8 and 10 [Brockelman et al., 1998]. The interbirth interval is between 2 and 3 years [Supriatna et al., 1994; Hodgkiss et al., 2009]. Javan gibbons live at average densities of approximately 2.5 groups/km² [Nijman, 2004], but this depends on resource abundance (especially the availability of figs), habitat disturbance, and elevation (with higher densities occurring at lower elevations) [Nijman, 2004; Kim et al., 2010], and they occupy a home range of between 15 and 37 ha [Kim et al., 2010].

Study Areas

We used 3 sites in our modelling: Ujung Kulon National Park, Halimun-Salak National Park, and Dieng Mountains (Fig. 1; Table 1). We chose these sites for the PVA as they represent the 3 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.

Ujung Kulon National Park

Ujung Kulon (6°45' S, 105°20' E) 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 300–560 Javan gibbons living in the park, and it is estimated that only 30–85 km² of the park remains as suitable habitat for them [Nijman, 2004].

Halimun-Salak National Park

Halimun-Salak (6°72' S, 106°46' E) has some of the largest remaining contiguous lowland forest on Java; however, small-scale and plantation agriculture, infrastructure development, gold

Table 1. Study site parameters

Area	Location	Status	Elevation, m above sea level	Total area, km ²	Suitable habitat for gibbons, km ²	Estimated population of gibbons
Ujung Kulon	Banten	National Park	0–620	760	30–85	300–560
Halimun-Salak	West Java	National Park	500–2,211	1,133	330–400	900–1,220
Dieng Mountains	Central Java	Unprotected forest	300–2,565	250	90–167	850

Sources: Rinaldi [2003]; Djanubudiman et al. [2004]; Nijman [2004]; Setiawan et al. [2012].

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 2 [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 330–400 km² 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 (7°12' S, 109°54' E) 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 4–5 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 90–167 km² of forest remains as suitable habitat for them [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., 2009] and is appropriate for modelling Javan gibbon populations as it is designed specifically for mammalian and avian populations with low fecundity and long lifespans [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, deterministic growth rate (det-r), mean stochastic growth rate (stoc-r), mean number of individuals for surviving populations (n), gene diversity, and the standard deviation (SD) for each. det-r is the projected growth rate of a population and excludes stochastic events. If stoc-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 variation across simulated populations (i.e., the standard deviation) 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 1 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 that the life history data on wild Javan gibbons are limited, we selected input values for the demographic

Table 2. Species-specific parameters: input values and rationale for values used in the baseline scenario(s)

Species-specific parameters	Input value	Rationale
Inbreeding depression	0.0	Inbreeding is unlikely to have a significant effect on populations of modelled sizes (all 3 populations >100) [Robert Lacy, in lit.; 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 when subadult or upon sexual maturity [Supriatna et al., 1994; Brockelman et al., 1998]
Breeding system	Long-term monogamy	Gibbons tend to exhibit long-term pair bond associations [Supriatna et al., 1994; Brockelman et al., 1998]
Age of first reproduction (years) for females/ males	8/10	Age of first reproduction tends to be between 8 and 10 for both males and females in wild populations of gibbons [Supriatna et al., 1994; Tunhikorn et al., 1994; Brockelman et al., 1998]
Percent adult females breeding	33 ± 17	The proportion of females breeding each year determines the interbirth interval This interval is reported to be 3 years in the wild, meaning 67% of adult females on average do not produce offspring [Supriatna et al., 1994; Brockelman et al., 1998]
Maximum number of broods per year	1	Female gibbons typically give birth to only 1 baby per year [Cocks and Campbell, 2008]
Maximum number of progeny per brood	1	Female gibbons typically give birth to only 1 baby as twins are rare [Cocks and Campbell, 2008]
Maximum age of reproduction (year) also equals maximum lifespan	25	Gibbons are assumed to be able to reproduce during 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 are no 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

EV, environmental variance.

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: 4 adult females, 4 juveniles; both Halimun-Salak and Dieng Mountains: 6 adult females, 6 juveniles). The rate of deforestation for both of the baseline scenarios was set at an estimated 1% annually [Nijman, 2004].

Table 3. Results from the baseline scenarios (500 iterations over 100 years) for 3 independent Javan gibbon populations on Java

Site and scenario	PE, %	stoc-r \pm SD	<i>n</i> -extant \pm SD	GD \pm SD, %
<i>Ujung Kulon (initial n = 430)</i>				
Low K (= 430)	100	-0.052 \pm 0.072	0 \pm 0	0 \pm 0
High K (= 817)	97.8	-0.046 \pm 0.072	99 \pm 68	97.8 \pm 0.7
No hunting or deforestation (low K)	0	0.009 \pm 0.054	387 \pm 49	98.5 \pm 0.2
No hunting or deforestation (high K)	0	0.008 \pm 0.053	424 \pm 55	98.6 \pm 0.2
Deforestation only (low K)	0	0.008 \pm 0.055	148 \pm 12	97.5 \pm 0.3
Hunting only (low K)	46.8	-0.029 \pm 0.086	164 \pm 116	96.8 \pm 3.3
<i>Halimun-Salak (initial n = 1,060)</i>				
Low K (= 1,060)	92.2	-0.036 \pm 0.068	108 \pm 77	98.4 \pm 0.5
High K (= 3,846)	44.4	-0.018 \pm 0.061	732 \pm 458	99.3 \pm 0.3
No hunting or deforestation (low K)	0	0.009 \pm 0.053	966 \pm 104	99.4 \pm 0.1
No hunting or deforestation (high K)	0	0.009 \pm 0.052	2,717 \pm 844	99.6 \pm 0.1
Deforestation only (low K)	0	0.009 \pm 0.053	372 \pm 21	99.0 \pm 0.1
Hunting only (low K)	0.4	0.001 \pm 0.054	786 \pm 235	99.3 \pm 0.3
Fragmented population	37.8	-0.029 \pm 0.054	87 \pm 50	97.0 \pm 1.0
Fragmented population, no hunting or deforestation	0	0.009 \pm 0.032	1,008 \pm 79	99.4 \pm 0.0
<i>Dieng Mountains (initial n = 850)</i>				
Low K (= 850)	100	-0.043 \pm 0.070	0 \pm 0	0 \pm 0
High K (= 1,298)	84.8	-0.036 \pm 0.068	176 \pm 98	98.7 \pm 0.3
No hunting or deforestation (low K)	0	0.009 \pm 0.053	792 \pm 82	99.3 \pm 0.1
No hunting or deforestation (high K)	0	0.009 \pm 0.053	1,172 \pm 147	99.5 \pm 0.1
Deforestation only (low K)	0	0.009 \pm 0.054	301 \pm 21	98.7 \pm 0.1
Hunting only (low K)	26.4	-0.015 \pm 0.060	396 \pm 246	98.9 \pm 0.5

Initial *n*, initial population size (for Ujung Kulon and Halimun-Salak the average of the low and high population estimate was used for analysis); carrying capacity (*n* = *K*) and increased carrying capacity; PE, probability of extinction; stoc-r, mean growth rate (mean stochastic population growth/decline rate); *n*-extant, mean number of individuals not extinct after 100 years; GD, genetic diversity or the mean “expected heterozygosity” remaining in the extant populations; SD, standard deviation; det-r for all 3 populations: 0.011.

We assume the populations of gibbons on Java are at or close to carrying capacity; however, we tested the baseline scenario with 2 carrying capacities for each site, 1 low and 1 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 1 group and then multiplied that by the average group size [Fan et al., 2013].

Currently, there are 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 lit., 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 the absence of these data, any decrease in 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 3 different populations to increased rates for both infant and dispersing gibbons (age groups 0–1 and 7–8 years; mortality rate 15 \pm 4%), as we assumed those 2 age ranges would be most sensitive to environmental pressures and stochastic events.

Fig. 2. Baseline scenario run for 500 iterations representing 100 years showing the mean number of extant individuals for the 3 independent populations. *Deforestation*: -1.0% annually; *Hunting*: Ujung Kulon: 2 infants/2 adult females; Halimun-Salak: 4 infants/4 adult females; Dieng Mountains: 4 infants/4 adult females. Low K (carrying capacity is equal to initial population size)

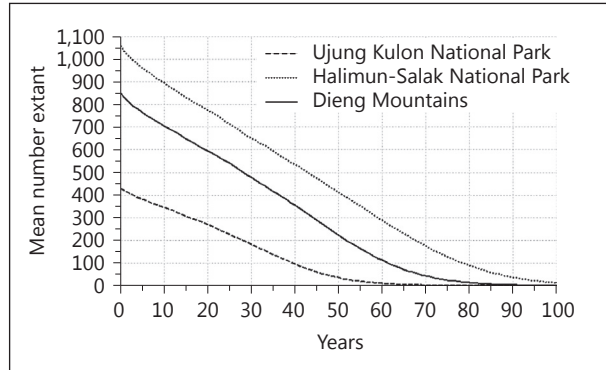
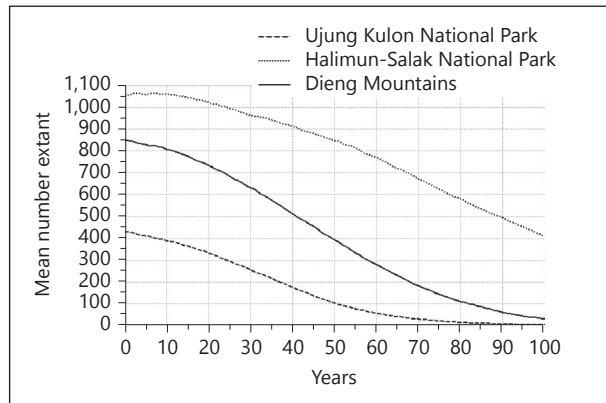


Fig. 3. Baseline scenario run for 500 iterations representing 100 years showing the mean number of extant individuals for the 3 independent populations. *Deforestation*: -1.0% annually; *Hunting*: Ujung Kulon: 2 infants/2 adult females; Halimun-Salak: 4 infants/4 adult females; Dieng Mountains: 4 infants/4 adult females. High K.



Area-Specific Scenarios

In our model, we assume all 3 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 are parameters that can be influenced by management practices or a change in human behaviour and are 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 (modelled as *Deforestation* in VORTEX) as an annual percentage decrease in carrying capacity ($= K \times (\text{proportion of previous year's forest cover remaining/year})$), 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 3 study sites (Table 3; Fig. 2), with high probabilities of extinction within

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: $15 \pm 4\%$) on each individual population

	PE, %			stoc-r \pm SD		
	baseline	inbreeding	high mortality	baseline	inbreeding	high mortality
<i>Ujung Kulon</i>						
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
<i>Halimun-Salak</i>						
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
<i>Dieng Mountains</i>						
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

PE, probability of extinction; stoc-r, mean growth rate (mean stochastic population growth/decline rate); SD, standard deviation; det-r for all 3 populations: 0.011.

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 3 populations in both baseline scenarios.

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 (Fig. 3). The population in Halimun-Salak remains relatively more stable with a 44% chance of becoming extinct in the next 100 years (Table 3).

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 stoc-r and increasing the probability of extinction (Table 4).

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 programmes, 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

Table 5. Results from area-specific scenarios for Ujung Kulon National Park, Halimun-Salak National Park, and Dieng Mountains

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

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 years; GD, genetic diversity or the mean "expected heterozygosity" remaining in the extant populations; SD, standard deviation; det-r for all three populations: 0.011. Carrying capacity (K) for Halimun-Salak and Dieng Mountains 10% increase in number.

(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, lead 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 3 smallest subpopulations going extinct within the next 100 years (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 2 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.

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 that the results of a PVA are only as accurate as the data on which they are based [Coulson et al., 2001; Marshall et al., 2009]. The current ecological and population data available on Javan gibbons are 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 are no data available 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. observation]. 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 on its natural resources [Whitten et al., 1996]. In addition, the

park (along with its better-known neighbour, Gunung Gede-Pangrango National Park) is an important watershed for western Java, including 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 al., 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 them 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 risk from 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 policies.

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 gibbon's 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 3 Javan gibbon populations are likely to go extinct if hunting and deforestation rates continue at the modelled rate. However, all 3 populations are still large enough to persist and maintain high genetic diversity over the next 100 years if deforestation and hunting can be minimized.

If Javan gibbons exist in populations of fewer than approximately 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 gib-

bons 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 patrols by rangers and an increase in local awareness regarding the protected status of Javan gibbons and the illegality of keeping gibbons 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. observation]. 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 [S. Jaima, N. Vincent, pers. observation] 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. Unfortunately, this creates a more complex trade network and is much more difficult to monitor and 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 an incentive to move forward with conservation efforts for Javan gibbons by highlighting the immediate threats and by 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 the survey data collected over the past 2 decades, it may be necessary to revisit and reassess the current management strategies for Javan gibbon conservation [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 the protected area network in poorly protected forests in central Java. Consequently one of the greatest contributions to the survival of Javan gibbons – and this

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 the 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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Disclosure Statement

The authors declare there is no conflict of interest.

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