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LETTER

Preventing Global Extinction of the Javan Rhino: Tsunami Risk and Future Conservation Direction

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Abstract

The Javan rhino (*Rhinoceros sondaicus*) is one of the most threatened mammals on Earth. The only remaining individuals live as part of a small population isolated in a single protected area, Ujung Kulon National Park, Java, Indonesia. Despite almost a century of studies, little is known about the factors that affect Javan rhino demography and distribution. National park officials require such information to identify conservation strategies and track the success and failures of these efforts; translocating selected individuals to establish a second population has been considered, but the risks must be weighed. We show that the 2013 global population of Javan rhinos was 62 individuals, which is likely near the site's carrying capacity. Our analysis of rhino distribution indicates that tsunamis are a significant risk to the species in Ujung Kulon, justifying the risks of establishing additional populations. Continued individual-based monitoring is needed to guide future translocation decisions.

Introduction

Biodiversity loss is one of the most important global environmental and human problems today (Díaz et al. 2006; Cardinale et al. 2012; Dirzo et al. 2014). Species face increasing and potentially synergistic threats from land conversion leading to habitat loss and fragmentation (Rybicki & Hanski 2013), nonnative species invasions (Vilà et al. 2011), overexploitation via local to global socioeconomic forces (Brashares et al. 2011; Wittemyer et al. 2014), and alterations of global physical processes, such as climate change (Moritz & Agudo 2013). Altering the seemingly inevitable path of many species extinctions will be difficult. A legal context for protection and enforcement is essential, as well as political will and stakeholder interest of those most affected. To garner support and to identify

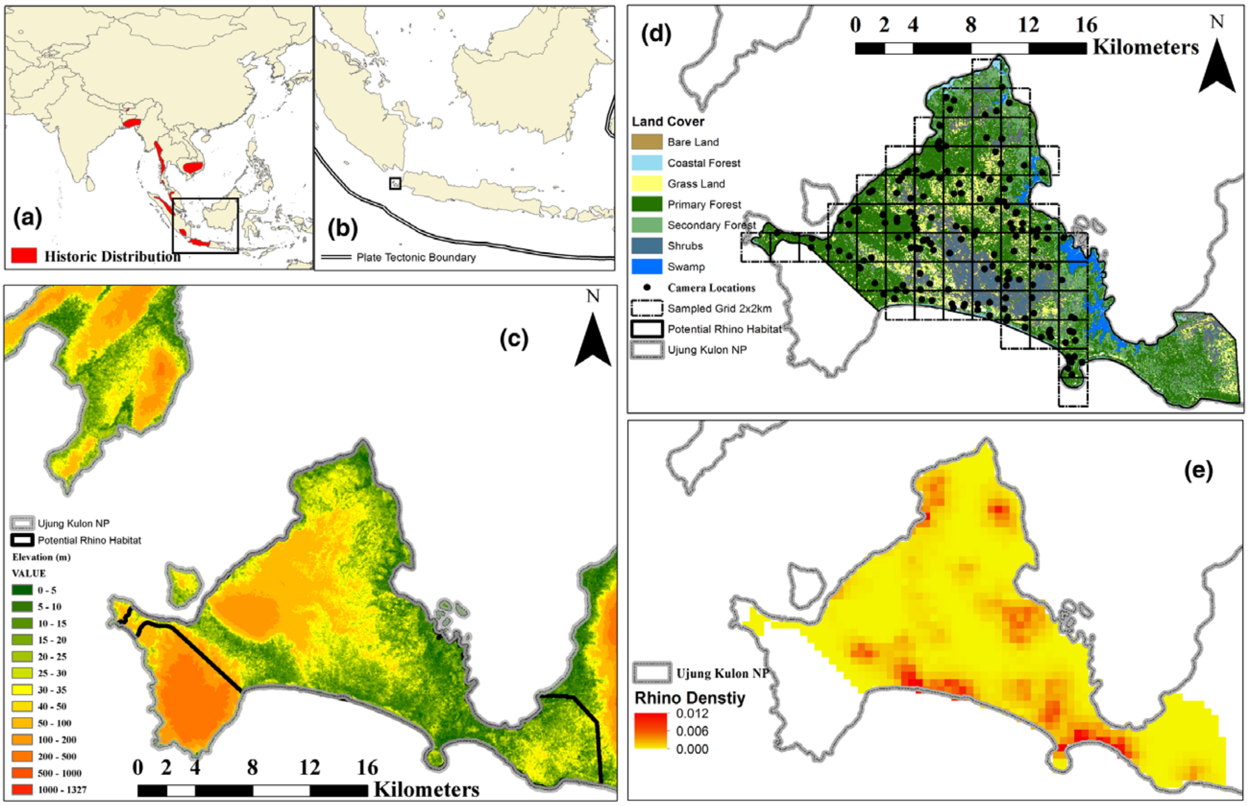

Figure 1 Spatial depiction of historic Javan rhino distribution, and current habitat, sampling, and density. Subplot a is the historic distribution of the Javan rhino based on museum specimens, adapted from Groves and Leslie (2011). The black square is enlarged in subplot b, which shows a black square highlighting the position of Ujung Kulon National Park on the western edge of the island of Java and is enlarged in subplots c–e. Subplots c and d define the physical context of the rhino habitat, the sampling framework, and locations of cameras. Subplot E is the predicted rhino density from our most parsimonious spatially explicit capture–recapture model.

effective conservation actions, basic fundamental science is need, which is not often available for many rare or threatened species.

Species with limited distribution and small population size are at the greatest risk of extinction (Diamond 1984; Johnson 1998). Conserving these species requires understanding both the causes and consequences of small and fractured populations (Caughley 1994). However, essential information (i.e., population size and distribution) required to understand the causes of population contractions and evaluate extinction risk is often unavailable (Jetz & Freckleton 2015). Our knowledge of even endangered charismatic megafauna (e.g., primates, carnivores, and rhinos) often lack detailed spatial information about where individuals occur or precise population estimates that are so important in directing effective conservation actions (Linkie et al. 2010; Groves and Leslie Jr 2011; McClintock et al. 2015; Schwitzer et al. 2015; Havmøller et al. 2016). Individual-based monitoring is especially important, as it provides a richness of demographic information (Clutton-Brock & Sheldon 2010) that can be critical in identifying effective conservation actions. The most critically endangered species require the most detailed and informative studies to know exactly where and how many individuals remain and to track these individuals to evaluate the successes and failures of conservation interventions.

Three of the five extant species of rhinoceros are listed as Critically Endangered on the IUCN Red List of Threatened Species (Javan (*Rhinoceros sondaicus*), Sumatran (*Dicerorhinus sumatrensis*), and Black (*Diceros bicornis*); IUCN 2016). While once numerous throughout Eurasia and Africa, rhinos are now almost entirely restricted to conservation areas, having been extirpated from much of their native range due to historical habitat loss and hunting, and more recently almost entirely due to poaching. Poaching of rhinos for their horn continues to be a major threat to all species despite the implementation of intensive protection measures (IUCN, 2016). The Javan rhino, having once occurred throughout Southeast Asia (Figure 1a; Groves & Leslie 2011), lost its mainland subspecies (*R. s. annamiticus*) with the poaching of the last individual from Vietnam in 2009 (Brook et al. 2014). This leaves a single, isolated population in Ujung Kulon National Park (UKNP) of Banten Province, Western Java, Indonesia (Figures 1b–e). Despite efforts, for close to a century, to study and monitor this population to inform conservation decision making, there has yet to be a reliable survey to accurately estimate the population size and distribution that simultaneously accounts for spatial coverage and incomplete counts.

Spatial population information is especially needed to evaluate the potential risks of tsunamis to rhinos and their habitat (Løvholt et al. 2014). UKNP is located on the south-western edge of the island of Java, adjacent to the Indonesian Sunda Arc (Figures 1a and b), an area of converging tectonic plates that commonly produces earthquakes, triggering tsunamis. More than 30 earthquakes of magnitude seven or greater have occurred in the last 30 years, causing tsunami run-up (vertical height above sea level at furthest point inland) along the coasts of Java and Sumatra, commonly at 20–30 m (Brune et al. 2010) with a maximum record of 49 m (Choi et al. 2006). Further, the neighboring Anak Krakatoa volcano lying in the Sunda Strait threatens with recent activity that also has the potential for causing tsunami inundation of UKNP (Bronto et al. 1990; Giachetti et al. 2012).

One proposal to reduce the extinction risk of the Javan rhino is to translocate individuals to establish a second and independent population (Ramono et al. 2009). Translocations to re-establish populations have become a key tool in rhino conservation efforts globally and are commonly used in conservation strategies for White (*Ceratotherium simum*), black and greater one-horned rhinos (*Rhinoceros unicornis*). Translocations are especially useful for rhino conservation as they can reduce density-dependent impacts on reproductive rates in the source population, in addition to triggering rapid increases in reproductive rates in re-established populations. However, translocation incurs risks to the translocated individuals and the source population, especially when removing a small number of individuals is a relatively large proportion of the total number of the species. This concern is exacerbated when there is significant uncertainty about the true size of the source population. For the conservation decision makers (i.e., UKNP administrators, the Indonesian Ministry of Forestry and Environment, and the Indonesian Director General for the Conservation of Natural Resource and the Environment) to weigh the risks of removing individuals from UKNP against not doing so, requires an understanding of the total population size and whether the population is near carrying capacity and thus depressing reproductive rates. Additionally, understanding the spatial distribution of Javan rhinos is needed to characterize the risk of the UKNP population to tsunamis and other natural and anthropogenic hazards. If translocation was agreed upon, knowing the population size and demography (e.g., sex ratio) would be essential in deciding on when and which individuals to translocate to maximize the success of the translocation and the recovery of UKNP's rhino population.

We developed a fine-scaled, individual-based spatial monitoring program to better understand the population ecology of the Javan rhino to reduce scientific uncertainties for policy makers to make informed conservation decisions. Our main objective is to outline a strategy to noninvasively monitor Javan rhino to (1) estimate the total population size, (2) identify spatial processes that affect their distribution, and (3) assess population-level tsunami risk. Second, we summarize all past rhino surveys in UKNP to consider population dynamics. By combining extensive video-sampling via remotely triggered cameras throughout UKNP with spatially explicit capture-recapture models (Borchers & Efford 2008), for the first time we characterize the distribution and size of the last remaining Javan rhino population in the world. This dataset represents the most comprehensive spatial information available for the entirety of the last remaining populations of one of the world's most threatened species.

Methods

We deployed infrared cameras throughout 90% of potential rhino habitat in UKNP from March to December, 2013 (178 camera locations; Figure 1d). Camera locations were chosen to maximize the spatial coverage by placing at least one camera per 2 × 2 km grid cell (excluding the southeastern area), while also maximizing the probability of multiple individual rhino detections by varying the number of cameras (0–3) in 1 × 1 km cells based on previously identified rhino sign (See Figures S1 and S2). UKNP protects the largest remaining tract of lowland tropical rainforest on the island of Java (38,000 ha) and is known to protect at least 29 mammals, more than 270 birds, and many species of reptile and amphibian (Haryono et al. 2016; UNESCO 2016).

Individual rhinos were identified from video-clips by three independent teams using diagnostic morphological features (e.g., size, horn shape, facial wrinkles, neck folds, skin pores, pigmentation, and sex; Griffiths 1993; Figure S3; see Appendix 1 for details); these datasets were found to have a high-level agreement (>95%). Coming together, the teams finalized a dataset that was fitted using a spatial capture–recapture model (Borchers & Efford 2008). We constructed a model set based on ecologically motivated hypotheses about influential factors on rhino detection, ranging, and density. We considered both individual (e.g., sex, age class [adult or subadult]) and environmental factors (e.g., climatic season, elevation, and slope; Table S1); the Supporting Information provides specific details on fitted models, model selection, and specific results.

Details of past rhino population surveys in UKNP were tabulated from primary and secondary literature found at the Rhino Resource Center (http://www.rhinoresourcecenter⟩.com/) and through Google Scholar (https://scholar.google.com/) and Thompson Reuters's Web of Science (https://apps.webofknowledge.com/) using the search terms "Javan Rhino" or "*Rhinoceros sondaicus.*" Additional literature was identified by UKNP officials from their own catalogue of studies conducted in the park.

Tsunami inundation and intersection with the predicted rhino distribution was done using ArcGIS v. 10.2 (ESRI, Redlands, CA, USA) by identifying elevation gradients (5–30 m) based on a digital elevation model of UKNP; elevations were chosen to capture feasible run-up levels and to identify levels that would most affect rhinos (see "Discussion" section). Areas of inundation only include elevation gradients below the specified threshold and connected to the shoreline. We consider inundation on all shorelines of UKNP and thus a maximum potential inundation, where a tsunami generated from the Sunda Arc would cause run-ups along the southern shorelines and of those within the Sunda Strait (Yatimantoro 2015).

Results

We obtained a total of 36,104 video clips, of which 5% (1,660) were Javan rhinos. The finalized dataset included 54 unique adult and subadult rhino (22 females, 32 males), which was used for subsequent modeling. A newly born calf was detected, but not included in the dataset. Using our most parsimonious model, we estimated that there were 62 rhinos (58–68, 95% CI) throughout all rhino habitat of UKNP in 2013 (Figure 1d). Rhino density varied spatially (Figure 1e) by elevation and distance to mud wallows, with elevation having more than twice the effect ($\beta = -4.48$ [−6.93 and −2.04, 95% CI]) than distance to a wallow ($\beta = -2.07$ [−3.14 and −0.99, 95% CI]). Mud wallows are critical for rhino's thermoregulation, as well as to avoid and remove ectoparasites, protect their skin, and for engaging in social chemical communication (Schenkel & Schenkel-Hulliger 1972; Amman 1985). We found the population sex ratio slightly skewed toward males at 0.59 (0.50–0.69, 95% CI). There was strong support that home range size varied between sexes and across climatic seasons (Tables S1 and S2); females had the smallest ranges in the dry season (14.20 km^2; June to July), while the largest range occurred for males in the transition period from the dry to wet season (105.53 km^2; September to October). Females had seasonal home ranges close to half the size of males.

We found that the highest density of rhino (upper 25%) occurs at an average elevation of 7 m at 108 m from the shoreline. The uppermost 50% and 75% rhino density occurs at an average elevation of 9 m at 412 m from the shoreline and 15 m elevation at 855 m from the shoreline, respectively. A tsunami run-up of 5 m could inundate all areas with the highest 20% of rhino density, while greater than 10 m could inundate more than 80% of the area with the highest 50% of rhino density (Figures 2 and 3). A tsunami run-up of 30 m would inundate essentially all areas where Javan rhino concentrate.

Based on population surveys starting in 1937, which suggested only 20–25 rhino, UKNP's population has seen significant increases in the 20th century (Figure 4). The primary monitoring strategy has been track surveys; using this method, the population was suggested to have tripled between 1965 and 1980, where it remained generally constant until 2001 and similar to our 2013 estimate. Sampling effort and spatial coverage for tracks surveys is unknown.

The first population estimate using individual identification and robust statistical inference (i.e., capture–recapture methods) was in 1993. Using approximately 60 camera locations distributed across a similar spatial extent as our study, an adult rhino population estimate was found to be 34 (25–52, 95% CI; Griffiths 1993). This estimate is considerably lower than track surveys during this time period and would suggest almost a doubling to our 2013 estimate. A follow-up camera survey carried out only in a portion of the previous survey area in 2009, estimated 32 rhinos (29–47, 95%; Hariyadi et al. 2011), however this would suggest a biologically unrealistic increase between 2009 and 2013. More likely was that the limited number of cameras and useable photos/videos for individual identification in 2009 led to an underestimate of the population.

Discussion

Our results indicate that the last remaining Javan rhino population consists of 62 animals, which given the limited availability of preferred habitat and apparent ceiling to the population size, is possibly near the carrying capacity. With the majority of the population concentrating near the shoreline, rhinos and their preferred habitat are highly exposed to risks of tsunami inundation. Annual

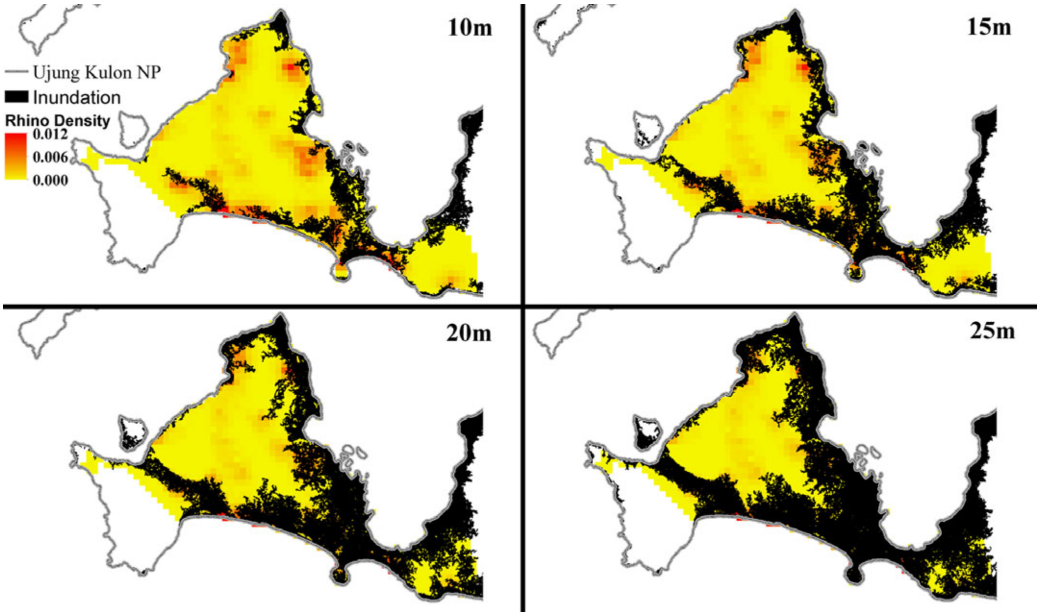

Figure 2 Predicted Javan rhino density and tsunami flood inundation at increasing run-up levels (10–25 m).

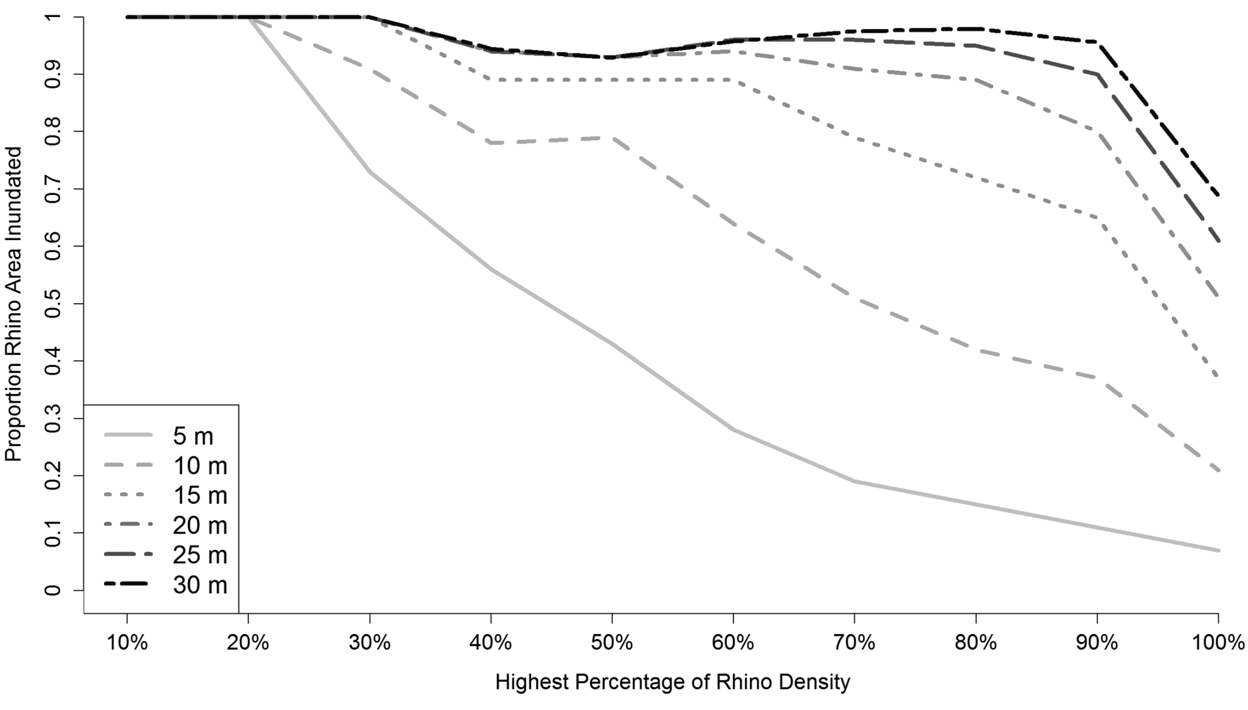

Figure 3 Inundation levels of the highest rhino density areas varying by tsunami run-up of 5–30 m.

probability predictions of an earthquake causing tsunami heights of greater than 3 m at UKNP is relatively small (up to 10%), but over longer time-frames (>100 years), tsunamis of 30 m are probable (Horspool et al. 2014; Løvholt et al. 2014). For most of Indonesia, tsunami run-up of 10 m is common (Hamzah et al. 2000), which would threaten the majority of areas of high rhino density, potentially leading to drowning or significant alteration of primary habitat. If the 2004 Sumatran-Andaman tsunami triggered at a similar position to Java instead of

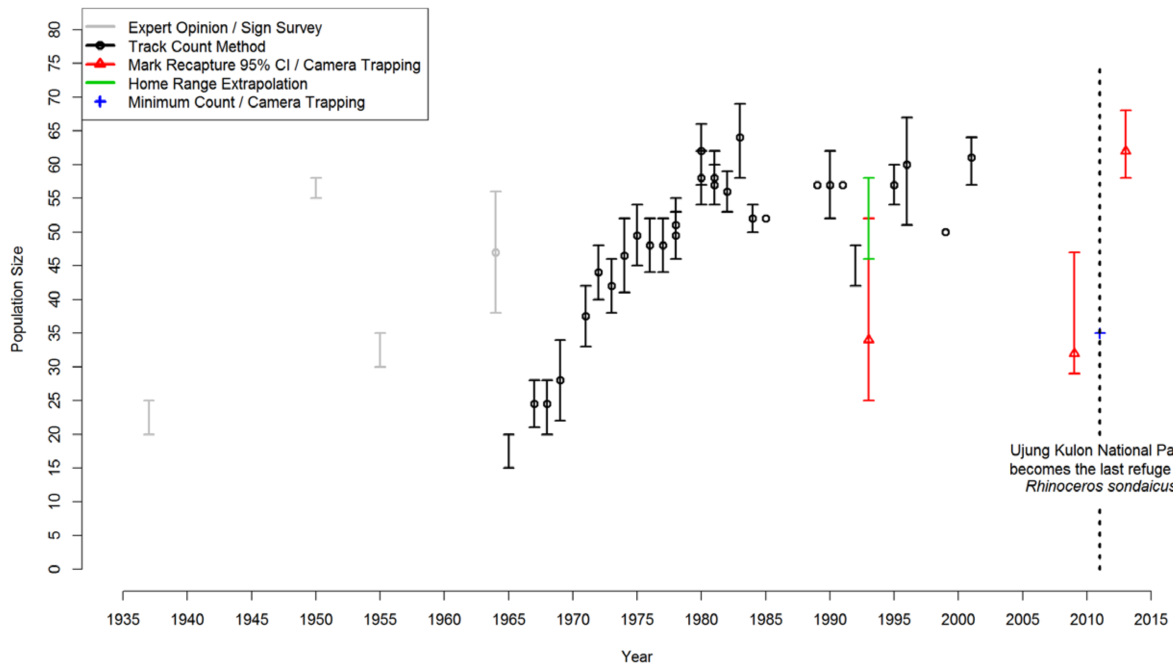

Figure 4 Population estimates of Javan rhino in Ujung Kulon National Park, Indonesia. Records indicate rhino have occurred in the park since before the Krakatoa volcano eruption of 1883. Track count intervals indicate lowest and maximum estimated number of rhinos. See Table S4 for references.

Sumatra, or the 2006 Java tsunami was slightly further west along the Sunda Arc, the wave height and subsequent run-up (average of 10 m and max of 48 m) would have put most, if not all, rhinos at risk from drowning (Choi et al. 2006; Fritz et al. 2007; NOAA 2017). One tsunami forecast using historic earthquakes of the Sunda Arc found that a likely earthquake would cause a maximum run-up of 11.6 m along the shoreline of UKNP (Yatimantoro 2015).

An additional tsunami threat comes from Anak Krakatoa volcano, the successor of Krakatoa volcano, which erupted in 1883 and was the most devastating in recorded history (Giachetti et al. 2012). Anak Krakatoa is not the size of Krakatoa, but predicted to produce considerable tsunamis (Giachetti et al. 2012). Based on its current size and continued growth, Anak Krakatoa could produce wave heights of 7.9–21.0 m if eruption occurred before 2040 and larger wave heights of 11.4–30.3 m likely thereafter with continued growth (Bronto et al., 1990). Natural hazards threatening UKNP's Javan rhinos are not limited to tsunamis, but include sea level rise, cyclones, and volcanic activity (Yusuf & Francisco 2009). Additional threats also include poaching, disease outbreaks (last experienced in the 1990s), and loss of forage due to the proliferation of invasive species (i.e., *Arenga obtusifolia*). Simply, the limited distribution and small population size of the Javan rhino makes the species highly vulnerable to extinction from a random demographic or environmental event.

Due to the past sampling concerns, it is unclear how to characterize the population dynamics of the Javan rhinos of UKNP, besides that the population has been small for a long time. Looking forward, our more robust monitoring strategy will provide accurate inference to population changes. This is essential for evaluating the success of conservation decisions. The detection of a calf, as well as many subadults in 2013 is a positive sign for the future population of Javan rhinos. Another positive sign is that recent surveys (December 2016) in the western part of UKNP around Mount Payung detected the presence of rhino for the first time, indicating the potential of additional animals and habitat not accounted for in our population estimate.

To significantly reduce Javan rhino extinction risk, human intervention and long-term investment will likely be needed. This includes both an increase in UKNP's carrying capacity via habitat management or food supplementation and establishing additional independent populations that are less exposed to tsunamis and other threats present at UKNP. In light of the multitude of risks facing the UKNP rhinos, the risks of removing a small number of individuals to establish a second population pales in comparison. Our individual-based spatial monitoring program can provide precise population estimates that will be needed by conservation decisions makers to decide when the UKNP has reached an acceptable size to remove individuals. Information on individual rhinos that can be ascertained from videos, such as sex, size, and body condition will also help identify the exact individuals to be translocated. Continuing monitoring of the UKNP population after translocation will also be essential to track the population and evaluate the success of habitat manipulations to increase the quality of rhino habitat.

Our results on population size, distribution, and vulnerability demonstrate that the risks to the Javan rhino population in UKNP are too large to solely depend on UKNP for the conservation of the species. Establishing additional populations will be essential for the long-term survival of the species and its progression towards a status in which they are not dependent on conservation interventions. Discussion on the establishment of a second population of Javan rhinos within the conservation community and the government of Indonesia has been ongoing for well over two decades. We have been lucky that to date no tsunami, volcanic eruption, major poaching event, or disease outbreak has occurred in UKNP. Our luck will not last forever. The UKNP rhino population is, and will continue to be, the most important asset in the long battle to save the species. However, we advise the Indonesian government and its partners to urgently develop and implement a program to establish additional Javan rhino populations. This program should leverage the extensive knowledge accumulated from translocation efforts of other rhino species (Emslie et al. 2009). This program should be built upon five basic ideas:

(1) Layout and stick to a timeline for establishing the second population and guidelines on how and when additional populations could be formed.
(2) Identify sites within Indonesia that are suitable for Javan rhino. Suitability must be measured in terms of habitat availability and socioeconomic support from the regional government and people. Clear and actionable conservation action plans that include appropriate habitat improvements and protection mechanisms must be rapidly implemented to ensure adequate conditions prior to translocation.
(3) Identify the number, sex ratio and preferably the individual rhinos from UKNP that will form the founder group to establish the second population.
(4) Further enhance conservation actions that will increase the reproductive rate of the UKNP population, especially via habitat improvements.
(5) Technical expertise, effort, cost, risk, support, and credit for such an ambitious and risky conservation strategy will need to be dispersed amongst many stakeholders to be successful, and as such will require a close and transparent collaboration.

Fine-scaled spatially explicit monitoring of the total extant population of critically endangered species is a challenging endeavor. However, recovering extremely small populations requires precise and accurate monitoring of where and how many animals remain. Overcoming the logistical and financial challenges often requires governmental, nongovernmental, and domestic and international organizational partnership, as exemplified by this work. Significant global human and financial investment is needed to ethically monitor, protect, and ultimately recover populations of threatened wild animals, such as the Javan rhino.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Figure S1. Camera locations and a 2 × 2 grid and 1 × 1 grid overlay used to distribute cameras to maximize the probability of detection of rhinos at multiple spatial locations.

Figure S2. Occurrence of rhino sign (e.g., active wallows, tracks, dung, and vegetation impacts) throughout Ujung Kulon National Park and kernel density analyses depicting different levels of smoothing.

Figure S3. Diagnostic characteristics used to distinguish individual rhinos, which in addition to sex and apparent body size include, (1) the horn shapes and position, (2) skin wrinkles around the eyes, (3) facial wrinkles, (4) neck curls, (5) the ear shapes and positions, (5) scratches, (6) scars, and also (7) skin tones.

Table S1. Spatial capture–recapture model selection results for the Javan Rhino in Ujung Kulon National Park

Table S2. Javan rhino predicted home range by sex and climatic season using the most parsimonious spatial capture–recapture mode

Table S3. Detection parameters from the most parsimonious model, including g_0 and σ

Table S4. Data on Javan rhino population estimates, survey method, and literature reference.

Movie S1

Movie S2

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