ECOLOGY

Poaching pressure on African rhinos is still at an all-time high

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The decrease in African rhino poaching incidents since 2015 has prompted many to praise the effectiveness of anti-poaching efforts. To test the validity of this statement, we calculated how far poachers moved on average from 2007 to 2022 to find a rhino in the context of the dwindling rhino densities. These calculations demonstrate that the total poaching pressure has remained persistently high since 2013. Given the concurrently declining arrest rates, our results show that the rhino protection practices of the past decade have been insufficient. Instead, we propose that rhinos can best be protected in small and well-monitored "safe havens" while focusing on long-term rhino horn demand reduction.

INTRODUCTION

Wildlife crime is driven by a rapidly expanding wealthy class in some cultures, where animal parts are viewed as medicine or status-enhancing luxury goods (*1*). The recent demand increase for rhino horn in China and Vietnam exemplifies this well, as it has caused a surge in rhino poaching in especially South Africa (*2*). In 2015, there were an estimated 20,000 white rhinos (*Ceratotherium simum*) and 5000 black rhinos (*Diceros bicornis*) worldwide, with 90% of the white rhinos and 40% of the black rhinos living in South Africa (*2*). Of these South African rhinos, 50% of the white and 20% of the black rhinos lived in Kruger National Park (NP) (Fig. 1A), making Kruger NP the world's most important area for the survival of African rhinos in the face of surging poaching pressures. Since 2015, the number of poached rhinos in Kruger NP has started to decrease continuously (Fig. 1A), which motivated South Africa's Minister of Environment to optimistically attribute this poaching decline to South Africa's "relentless" anti-poaching efforts in her last four yearly press statements (*3*).

However, South Africa's recently published rhino population censuses from Kruger NP paint a far grimmer picture, as they also show a plummeting trend of the rhino population coinciding with the decline in poaching numbers (Fig. 1). These figures suggest an alternative explanation for this decline in poaching: There are not fewer poachers, but fewer rhinos to poach.

RESULTS

We set out to determine whether fewer poachers or fewer rhinos are causing the recent poaching decline. Our calculations follow from the simple premise that it takes longer for a poacher to "blindly" search for a rhino when there are fewer rhinos, comparable to fishermen searching for tuna (*4*). We demonstrate that these "naive" poachers' average movement distance until first encountering a rhino (viz., poaching effort) increases linearly with the inverse of rhino density (see Materials and Methods). Because of this relationship and the dwindling Kruger NP rhino numbers, the average poaching effort has been increasing markedly and continuously since 2015 (Fig. 2A). When multiplying this average poaching effort with the number of poaching incidents in Kruger NP to retrieve the total traversed distance by successful poacher groups (viz., poaching pressure), we show that the poaching pressure on rhinos in Kruger NP has been consistently high since 2013 (Fig. 2B).

DISCUSSION

Our results demonstrate that the decline in poached rhinos in Kruger NP cannot be attributed to a reduced poaching pressure, but rather to a constant poaching pressure with dwindling resources (i.e., rhinos). Nonetheless, the number of poachers who were arrested has decreased markedly since 2017 (*5*). Given that South Africa's anti-poaching efforts have not decreased since then (*6*), these numbers indicate that the arrest rate is mostly dependent on the absolute number of poached rhinos. This demonstrates that the arrest rate of poachers moving through the reserve is low (Fig. 2D) and that arrests probably merely follow after shots have been fired or criminal investigations have taken place (Fig. 2C).

In reality, rhino poachers in Kruger NP are also most of the time naive to the locations of individual rhinos, forcing them to search for rhinos themselves (*7*), which already took poachers an average of 3.35 days to locate a single rhino inside Kruger NP in 2014 (*8*). Even park personnel are naive to the locations of individual rhinos in Kruger NP, which forced SANParks to use a costly aircraft to scout for rhinos during their entire rhino dehorning operation (*9*). Our model does obviously simplify the actual movement behavior of rhino poachers in Kruger NP, as in reality poachers will also try to locate rhino tracks, middens, and drinking spots (*7*). This makes it, for example, easier for poachers to locate rhinos during a full moon (as the visibility is better) and during dry periods (as there are fewer drinking spots) (*7*). However, also in these situations, the time it takes to locate a rhino is still dependent on the rhino density, so it only introduces variability in the poaching effort and does not violate our model assumptions.

Since the effort for naive poachers to find a rhino in Kruger NP has been increasing so rapidly recently (Fig. 2A), poachers will likely further step up their recent shift to other reserves with higher rhino densities (*5*). Consequently, collusion with anti-poaching

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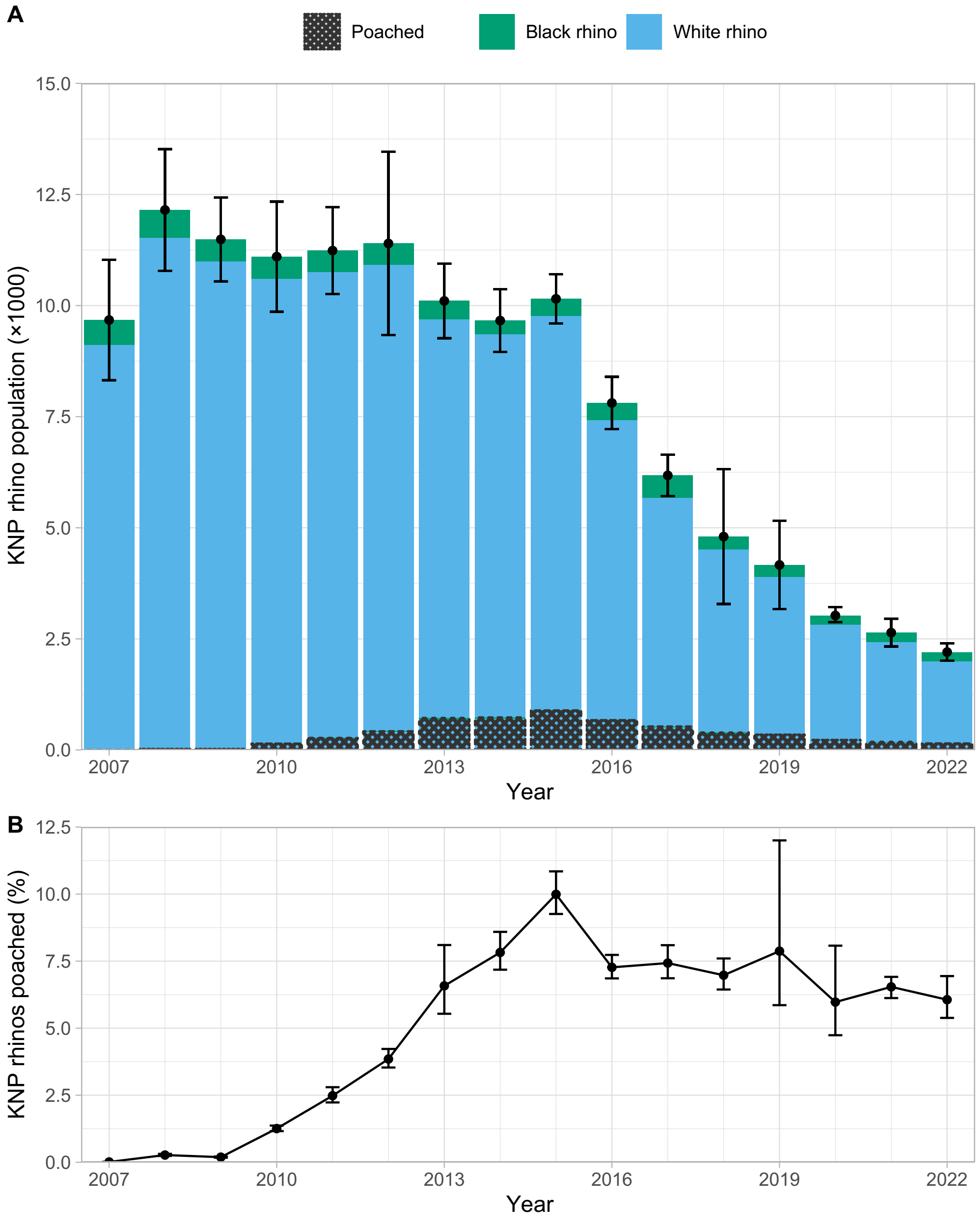

Fig. 1. Rhino population and poaching in Kruger National Park (KNP) from 2007 to 2022. Source: SANParks. Alive and poached white and black rhino population (**A**) and total percentage poached (**B**), both with population confidence limits.

personnel (*6*, *10*) is growing in importance for poachers as well. Considering that the average movement distance for poacher groups to find a rhino increased from 7 km in 2015 to 29 km in 2022 (Fig. 2A) and will continue to increase with a declining rhino population, blindly roaming around to find a rhino is becoming a less and less rewarding strategy. This extra time that poacher groups need to search probably means that there is now substantially more money available than in 2015 to bribe conservation officers for their assistance in poaching a rhino. We thus forewarn other rhino-harboring reserves of increased poaching pressures in the near future and prompt the anti-poaching authorities for a likely increase in attempted briberies and extortions. Unfortunately, these expected increases in corruption cases in Kruger NP and poaching numbers in other South African reserves have recently been reported to already be taking place (*10*).

Most of all, we urge the authorities to cease considering the decline in absolute poaching incidents as a positive sign (*3*, *6*, *11*). The massive reduction in the African rhino population over the past 10 years, combined with the approximately constant yearly fraction of rhinos having been poached (Fig. 1B), implies that the anti-poaching efforts have not been enough to prevent a strong

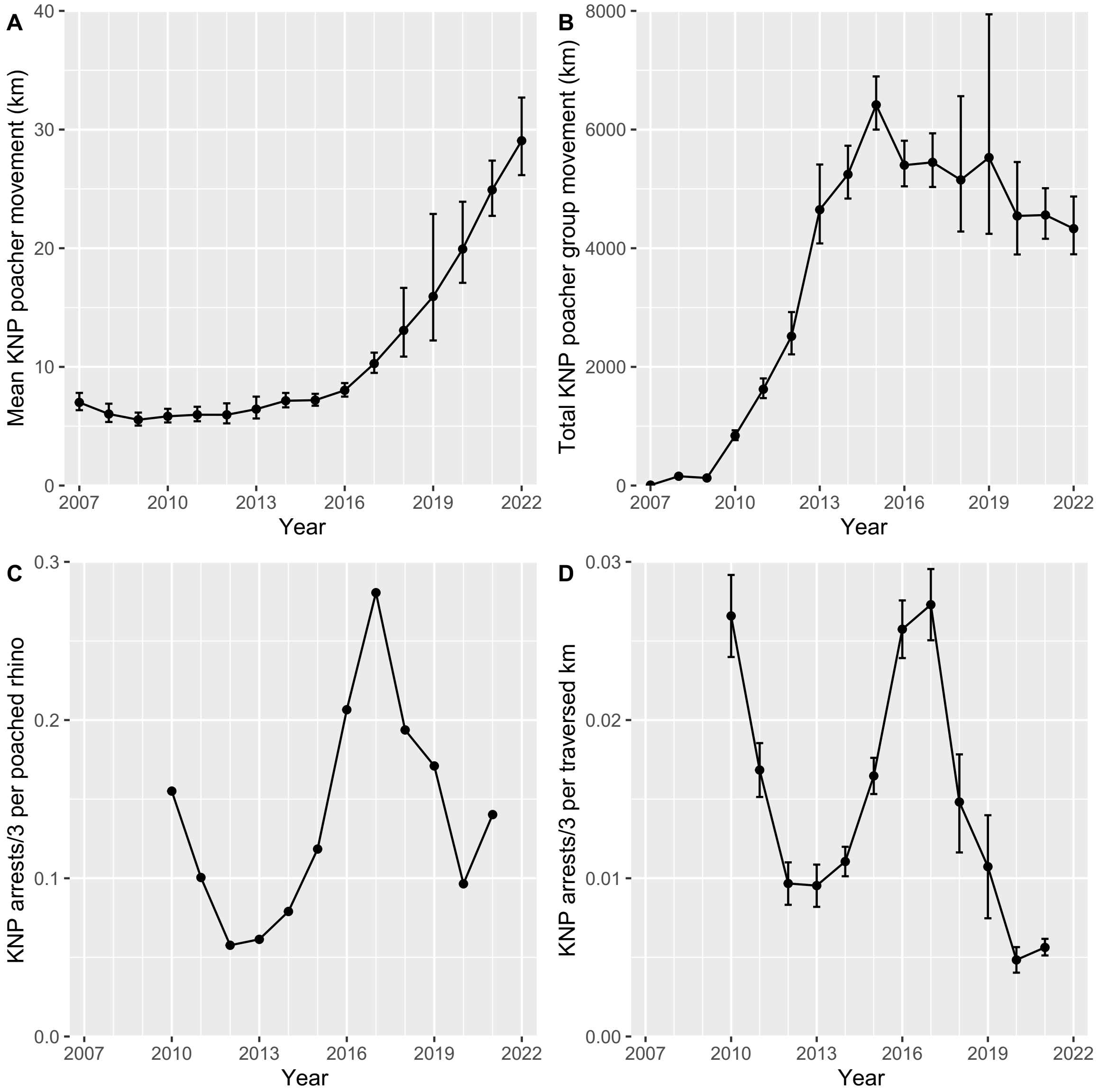

Fig. 2. Modeled rhino poaching statistics in Kruger National Park (KNP) from 2007 to 2022. Rhino poaching effort (**A**), pressure (**B**), arrests (*5*) per poached rhino (**C**), and arrests per traversed kilometers (**D**). Both arrest rates were corrected for the average poacher group size of 3 (*8*). These statistics were modeled directly from the rhino population and poaching data (Fig. 1A); see Materials and Methods.

population decline (Fig. 1A). If the anti-poaching efforts would have been effective in reducing the number of rhino poaching incidents, then it should have caused an additive decline in the number of rhino poaching incidents on top of the effect caused by the dwindling rhino density, which it did not (Fig. 2B). Moreover, this poaching pressure is not likely to decrease in the near future, because of the high price that consumers are willing to pay for rare animal products, which can drive the species to global extinction (*12*). The recent changes in South Africa's anti-poaching strategy to prioritize situational awareness, access control, and dehorning of all rhinos in Kruger NP (*11*) may very well lower the poaching pressure to some extent (*13*). However, considering that poachers were not demotivated by a four times less efficient rhino horn harvesting rate over the past 7 years (Fig. 2A) to warrant a reduction in poaching pressure (Fig. 2B), the reduction in the amount of keratin carried by the rhinos needs to be substantial and regularly maintained before it will discourage poachers enough to abandon Kruger NP for reserves that still have horn-carrying rhinos (*13*).

We posit that the key to the survival of African rhinos as a species lies in the protection of as many rhinos as possible in small and well-monitored "safe havens" while focusing on long-term demand reduction for rhino horn in consumer countries (*11*, *14*). The species' potential to rebound from this crisis is exemplified by the Southern white rhino's astounding recovery from less than 100 individuals in 1895 to more than 20,000 in 2015 (*2*). So if, in the future, the demand for rhino horn has diminished, rhinos can safely roam the wide African savannas again.

MATERIALS AND METHODS

Overview

For this study, we have developed a mathematical model to calculate the probability that a poacher encounters a rhino after moving a certain distance through a reserve. First, we describe our model's definitions and assumptions. Second, we validate the reliability of our model using poacher and rhino movement simulations with varying movement parameters and rhino densities. Last, we use our model to calculate the poaching pressure and effort in Kruger NP over the years with the actual rhino population and poaching data.

Definition

Given the solitary behavior of adult African rhinos, we assume n regularly (following the ideal free distribution in a homogeneous area) or uniformly distributed rhinos in a reserve with a poacher who is naive to the rhinos' locations. The probability P for a poacher to encounter a rhino is then

$$P(x \geq 1) = 1 - (1 - \phi)^n$$

where $x \in \mathbb{N}_0^n$ is the number of encountered rhinos by a poacher in the reserve, $n \in \mathbb{N}_0$ is the total number of rhinos in the reserve, and $\phi \in \mathbb{R}_0^1$ is the fraction of the area observed by a poacher, with the probability density function (PDF) of $P(x \geq 1)$ for ϕ being

$$\frac{\partial P(x \geq 1)}{\partial \phi} = n(1 - \phi)^{n-1}$$

This results in the mean $\mathbb{E}(\phi)$ (Fig. 3) and variance $\mathbb{V}(\phi)$ of the observed fraction of the area ϕ to first encounter a rhino

$$\mathbb{E}(\phi) = \int_{\phi=0}^{1} \phi \frac{\partial P(x \geq 1)}{\partial \phi} \partial \phi = \frac{1}{n+1}$$

$$\mathbb{V}(\phi) = \int_{\phi=0}^{1} \left[\phi - \mathbb{E}(\phi)\right]^2 \frac{\partial P(x \geq 1)}{\partial \phi} \partial \phi = \frac{n}{(n+1)^2(n+2)}$$

When a poacher has a constant exploratory movement process until first encountering a rhino, then the moved distance relates linearly to the observed fraction ϕ. For a sedentary poacher who has an omnidirectional observation radius r,

$$\phi = \frac{A_p}{A_t} = \frac{\pi r^2}{A_t}$$

where $A_p \in \mathbb{R}_0^{A_t}$ is the unique area observed by a poacher, $A_t \in \mathbb{R}_+$ is the total area of the reserve, and $r \in \mathbb{R}_0$ is the observation circle radius of a poacher, which is a special case of a poacher who moves a distance s in a straight line

$$A_p = \pi r^2 + 2rs$$

where $s \in \mathbb{R}_0$ is the distance moved by a poacher, which is again a special case of a poacher who changes directions uniformly at every distance τ

$$A_p = \pi r^2 + 2rs - 2r\tau \sum_{j=1}^{\frac{s}{\tau}-1} \sum_{k=1}^{j} \left[\left(\frac{\overline{A}_o}{2r\tau}\right)^k\right]$$

$$A_p = \pi r^2 + 2rs - 2r\tau \sum_{j=1}^{\frac{s}{\tau}-1} \left[\frac{\left(\frac{\overline{A}_o}{2r\tau}\right)^{j+1}}{\frac{\overline{A}_o}{2r\tau} - 1} - \frac{1}{\frac{\overline{A}_o}{2r\tau} - 1} - 1\right]$$

$$A_p = \pi r^2 + 2rs - 2r\tau \left\{\frac{\frac{1}{\frac{\overline{A}_o}{2r\tau} - 1}\left[\left(\frac{\overline{A}_o}{2r\tau}\right)^{\frac{s}{\tau}+1} - \left(\frac{\overline{A}_o}{2r\tau}\right)^2\right] - \left(\frac{s}{\tau} - 1\right)}{\frac{\overline{A}_o}{2r\tau} - 1} - \left(\frac{s}{\tau} - 1\right)\right\}$$

$$A_p = \pi r^2 + 2rs - \frac{2\overline{A}_o r\left(2r\tau\left\{\tau\left[2^{-\frac{s}{\tau}}\left(\frac{\overline{A}_o}{r\tau}\right)^{\frac{s}{\tau}} - 1\right] + s\right\} - \overline{A}_o s\right)}{(\overline{A}_o - 2r\tau)^2}$$

where $\overline{A}_o \in \mathbb{R}_0^{2r\tau}$ is the mean overlap in the observed area by a poacher per turn, $\tau \in \mathbb{R}_r^s$ is the distance between subsequent turns by a poacher, $k \in j \in \mathbb{N}_+$ is the poacher turn identifier, where the overlap in the observed area A_o (Fig. 4) is

$$A_o = \begin{cases} r^2 \tan\left(\frac{|\alpha|}{2}\right), & \text{if} |\alpha| \leq 2\arctan\left(\frac{\tau}{r}\right) \\ \tau\left[2r - \frac{\tau}{\tan\left(\frac{|\alpha|}{2}\right)}\right] - \tan(\pi - |\alpha|)\left[r - \frac{\tau}{\tan\left(\frac{|\alpha|}{2}\right)}\right]^2, & \text{if} |\alpha| > 2\arctan\left(\frac{\tau}{r}\right) \end{cases}$$

where $\alpha \sim \mathcal{U}(-\pi, \pi)$ is the turning angle of a poacher, so that the mean overlap in the observed area $\overline{A}_o$ becomes

$$\overline{A}_o = \frac{\int_{\alpha=0}^{2\arctan\left(\frac{\tau}{r}\right)} r^2 \tan\left(\frac{\alpha}{2}\right) \partial\alpha + \int_{\alpha=2\arctan\left(\frac{\tau}{r}\right)}^{\pi} \tau\left[2r - \frac{\tau}{\tan\left(\frac{\alpha}{2}\right)}\right] - \tan(\pi - \alpha)\left[r - \frac{\tau}{\tan\left(\frac{\alpha}{2}\right)}\right]^2 \partial\alpha}{\pi}$$

With these assumptions, the mean distance moved by a poacher when first encountering a rhino equals

$$\mathbb{E}(A_p) = \frac{A_t}{n+1}$$

In real-world situations, there is a negligible chance of instantaneously encountering a rhino when entering a reserve, which translates to

$$\lim_{\frac{\pi r^2}{\frac{A_t}{(n+1)}} \to 0} \mathbb{E}\left[2rs - \frac{2\overline{A}_o r\left(2r\tau\left\{\tau\left[2^{-\frac{s}{\tau}}\left(\frac{\overline{A}_o}{r\tau}\right)^{\frac{s}{\tau}} - 1\right] + s\right\} - \overline{A}_o s\right)}{(\overline{A}_o - 2r\tau)^2}\right] = \frac{A_t}{n+1}$$

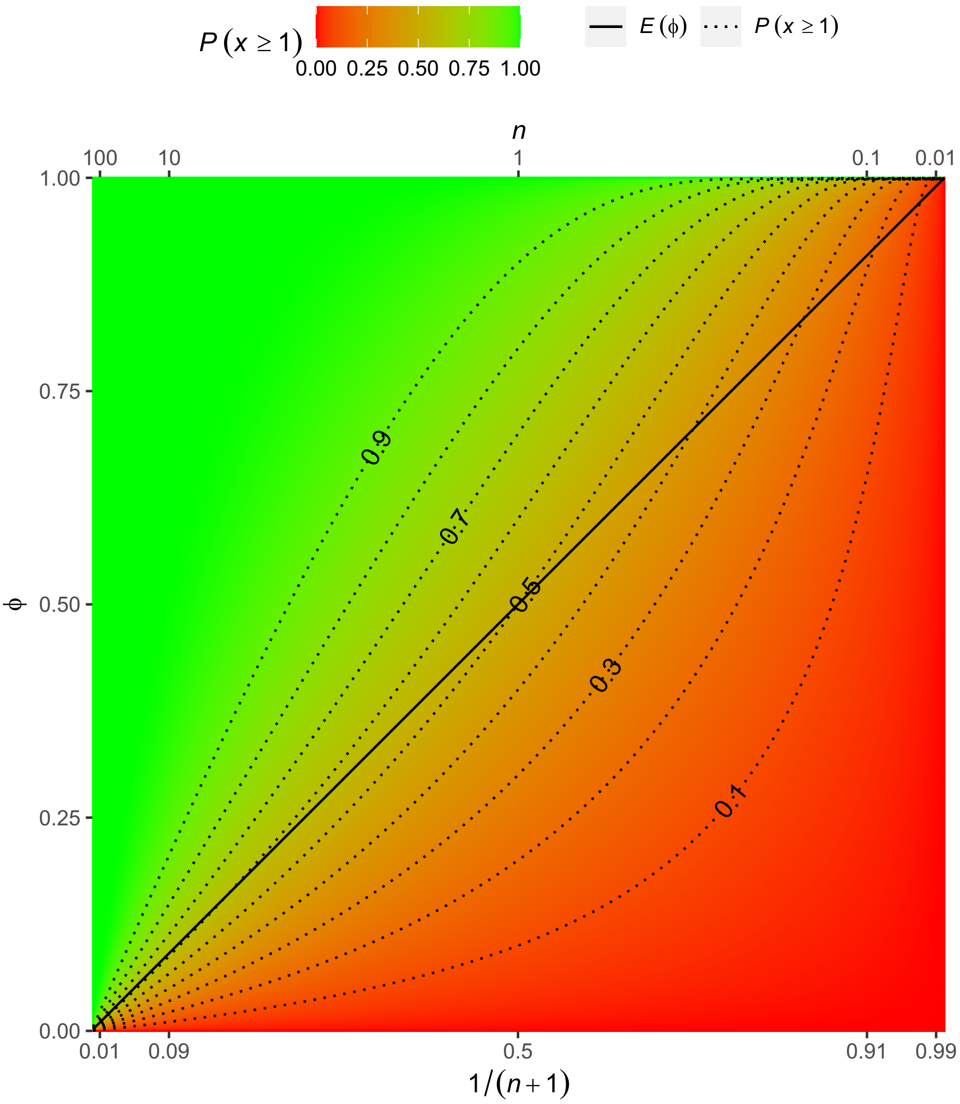

Fig. 3. Rhino encounter probability versus the number of rhinos. The probability for a poacher to encounter a rhino [$P(x \geq 1)$] as color and dotted contour lines, versus the total number of rhinos in a reserve (n) on the upper x axis and $1/(n+1)$ on lower, versus the fraction of area observed by a poacher (ϕ) on the y axis, with the mean observed fraction of the area to first encounter a rhino [$E(\phi)$] as a solid line.

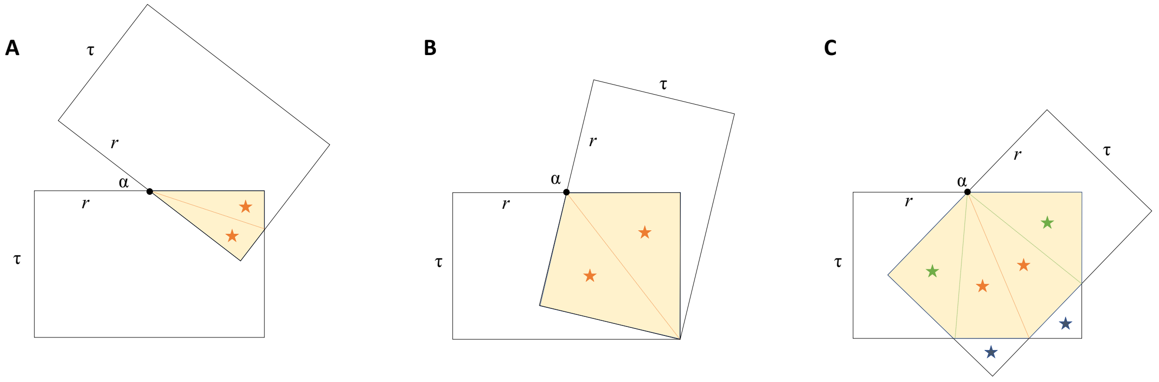

Fig. 4. Overlap in the observed area by a poacher (A_o) for three different turning angle (α) ranges. $\alpha < 2\arctan\left(\frac{\tau}{r}\right)$ (**A**), $\alpha = 2\arctan\left(\frac{\tau}{r}\right)$ (**B**), and $\alpha > 2\arctan\left(\frac{\tau}{r}\right)$ (**C**).

Moreover, in reasonably unobstructed environments like African savannas, poachers can move in semi-straight lines to maximize their observed areas

$$\lim_{\substack{\tau \to s \\ \frac{\pi r^2(n+1)}{A_t} \to 0}} \mathbb{E}(s) = \frac{A_t}{2r(n+1)}$$

$$\lim_{\substack{\tau \to s \\ \frac{\pi r^2(n+1)}{A_t} \to 0}} P(x \geq 1) = 1 - \left(1 - \frac{2rs}{A_t}\right)^n$$

$$\lim_{\substack{\tau \to s \\ \frac{\pi r^2(n+1)}{A_t} \to 0}} \frac{\partial P(x \geq 1)}{\partial s} = \frac{2nr\left(1 - \frac{2rs}{A_t}\right)^{n-1}}{A_t}$$

$$\lim_{\substack{\tau \to s \\ \frac{\pi r^2(n+1)}{A_t} \to 0}} s = \frac{A_t\left[1 - \sqrt[n]{1 - P(x \geq 1)}\right]}{2r}$$

Validation

Poacher interturn distances

To test the sensitivity of our aforementioned calculations about poacher movement distance to stochasticity in poacher interturn distances (distance between subsequent turns by poachers), we developed a movement simulation model in R 4.3.1 (*15*). In this model, we simulated a single moving poacher with 10,000 random initializations on a two-dimensional toroid (to avoid lower local rhino densities near the edges) with the approximate dimensions of Kruger NP (360 km × 55 km), together with varying numbers of sedentary rhinos. We terminated the simulations after the poacher arrived within a predetermined distance (representing the observation radius) from a rhino, thereby recording the moved distance as output. We sampled the interturn distances of the poacher from four statistical distributions, which we parameterized in such a way that the mean values μ were identical (Fig. 5):

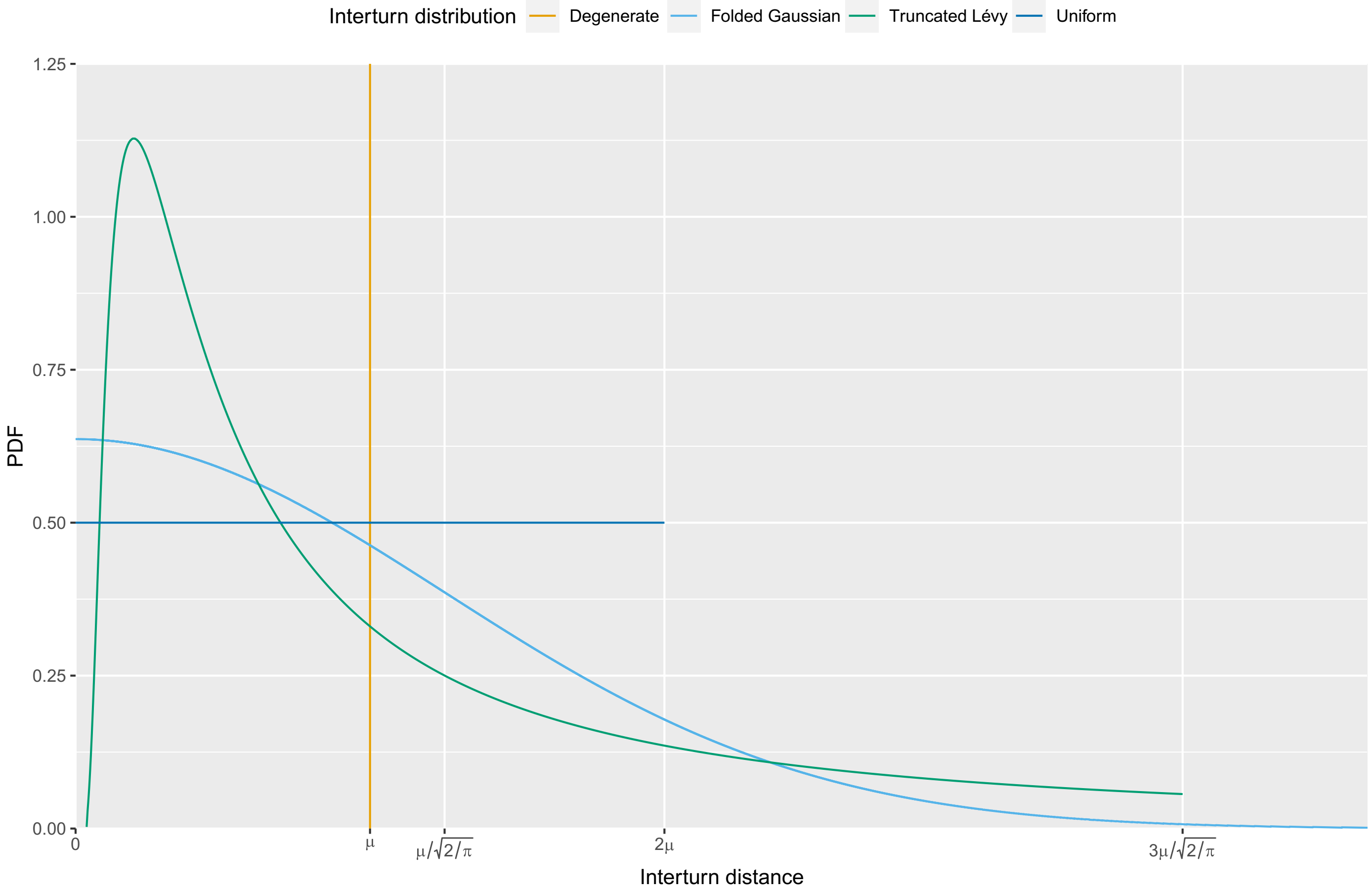

Fig. 5. The probability density function (PDF) of our four modeled distribution types for the interturn distances (distance between subsequent turns) of a poacher, all with identical mean (μ) values.

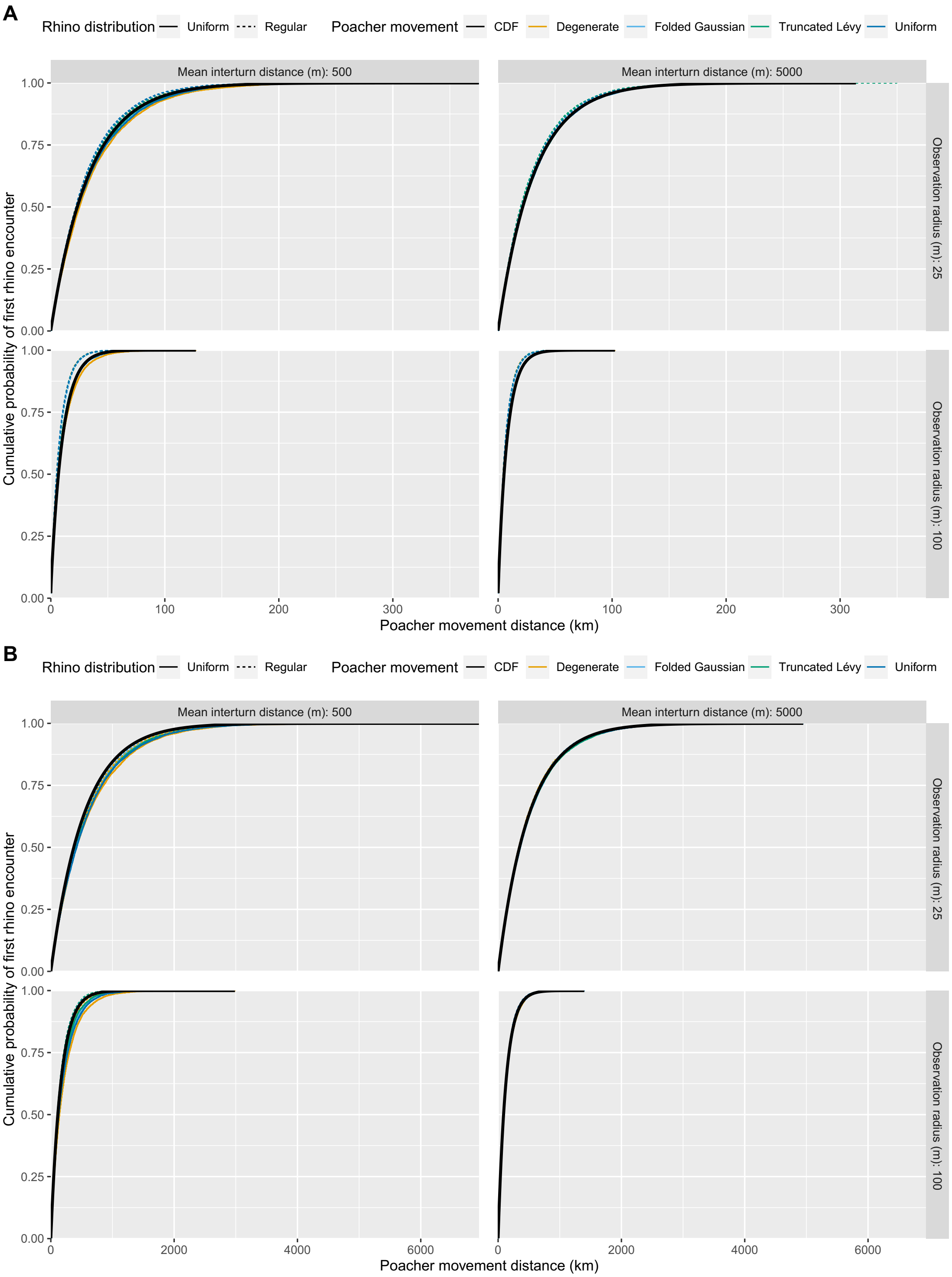

Fig. 6. Model predictions of poacher movement distance compared to the simulation results of stochastic poacher movement. Model predictions [cumulative distribution function (CDF)] and simulation results of the poacher's cumulative probability to encounter first rhino (*y* axis) given the moved distance (*x* axis) for various poacher interturn distance distribution types (line colors), rhino distribution types (line types), observation radii (horizontal panels), mean interturn distances (vertical panels), and rhino densities in Kruger National Park: 12,672 rhinos [$1.25^2 = 1.5625$ km^2 per rhino, (**A**)] and 792 rhinos [$5^2 = 25$ km^2 per rhino, (**B**)].

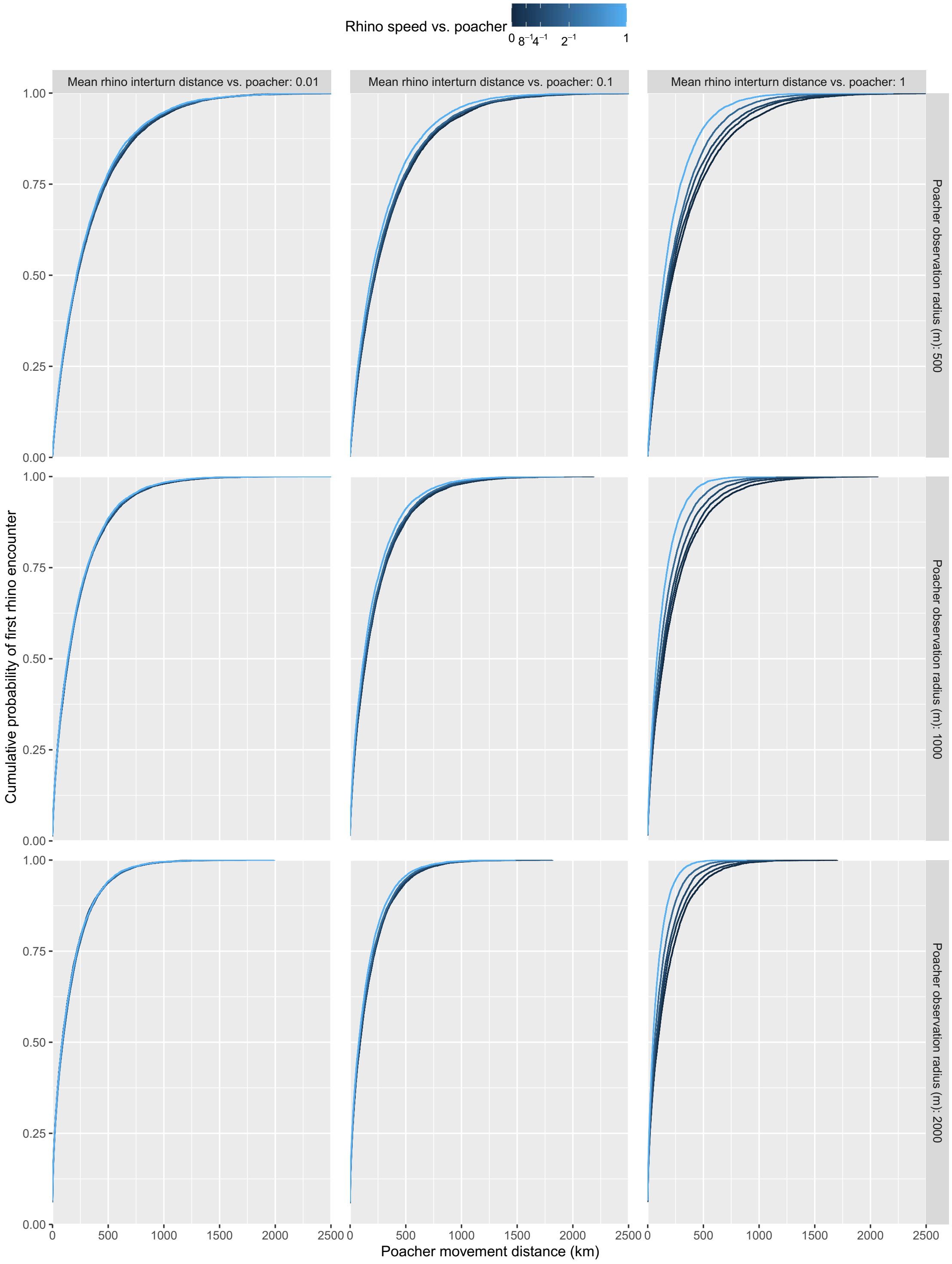

Fig. 7. Model predictions of poacher movement distance compared to the simulation results of stochastic rhino movement. Simulation results of the poacher's cumulative probability to encounter a single rhino (*y* axis) given the moved distance (*x* axis) for various rhino speeds relative to the poacher (line colors), observation radii (horizontal panels), and mean rhino interturn distances relative to the poacher (vertical panels).

Degenerate,

$$s = \mu$$

folded Gaussian,

$$s \sim \mathcal{N}_f\left(l = 0, \mu = c\sqrt{\frac{2}{\pi}} \right)$$

truncated Lévy,

$$s \sim \mathcal{L}_t\left(l = 0, m = \frac{3\mu}{\sqrt{\frac{2}{\pi}}}, \mu = \frac{e^{-\frac{c}{2m}}\sqrt{\frac{2cm}{\pi}}}{erfc\sqrt{\frac{c}{2m}}} - c \right)$$

and uniform,

$$s \sim \mathcal{U}\left(l = 0, \mu = \frac{m}{2} \right)$$

where μ is the mean parameter, l is the distribution-specific location parameter, c is the distribution-specific scale parameter, and m is the distribution-specific maximum parameter.

Our calculated cumulative distribution function (CDF) of the poacher's moved distance until first encountering a rhino corresponds well with the cumulative probability of our simulations in which the poacher's interturn distance is sampled from four different distributions (Fig. 6). We tested this for all of the following parameter combinations:

1) uniform and regular rhino distribution,
2) high (0.64 km^{-2}) and low (0.04 km^{-2}) rhino density $\frac{n}{A_t}$,
3) large (5000 m) and small (500 m) mean poacher interturn distance μ, and
4) large (100 m) and small (25 m) poacher observation radius r.

Rhino movement patterns

To also test the sensitivity of our aforementioned calculations about poacher movement distance to varying movement characteristics of rhinos, we performed the same movement simulations as before but now with Brownian moving rhinos at varying speeds and mean distances between their turns. Furthermore, to reduce computational resources and because we already successfully showed that the following variables did not invalidate our model predictions, we

1) reduced the length and width of the toroid arena to 10%,
2) only simulated one rhino per simulation,
3) increased the poacher's observation radii to 500, 1000, and 2000 m,
4) set the poacher interturn distance to 2500 m, and
5) set the poacher speed to 2500 m per hour.

For all our simulated poacher observation radii, the movement of rhinos hardly affected the cumulative probability of the poacher's moved distance before encountering the first rhino (Fig. 7). The cumulative probability of moved distance only deviated from the situation with sedentary rhinos when rhinos moved both with very high speeds (comparable to the poacher's speed) and large mean interturn distances (also comparable to the poacher). However, these high speeds and large interturn distances are unlikely to occur often in reality as rhinos spend most of their time resting and foraging while moving slowly and tortuously (*16*).

Calculations

To calculate the poaching pressure (viz., the total moved distance by poachers; Fig. 2B), we used the official SANParks rhino poaching and population statistics from Kruger NP (Fig. 1A). We used our formula for expected poacher movement distance $\mathbb{E}(s) = \frac{A_t}{2r(n+1)}$, with 19,623 km^2 as Kruger NP's area A_t and 0.15 km as observation radius r (an expert's estimate for the mixed savanna landscape of Kruger NP by taking into account all senses and cues that poachers use to locate rhinos). Note that this estimated value for r only affects the absolute values of poaching pressure but does not affect its trend over time. All yearly rhino population counts from Fig. 1A took place in mid-September, with the accompanying poaching data being the poached rhinos from 16 September of the previous year until 15 September of the current year. The error bars in Figs. 1 (A and B) and 2 (A, B, and D) constitute the confidence limits of SANParks' rhino population estimates. When calculating the poaching pressure, we assumed that the poaching incidents were equally spaced in time over the year and that the rhino population changed linearly over the year as well. That way, we calculated rhino poaching pressure (Fig. 2B) of year y as

$$\sum_{i=0}^{p-1} \frac{A_t}{2r\left(n_{y-1} + i\frac{n_y - n_{y-1}}{p} + 1 \right)}$$

where $i \in \mathbb{N}_0$ is the yearly poaching incident identifier, $p \in \mathbb{N}_+$ is the total recorded poaching incidents from year $y - 1$ to y, $n_{y-1} \in \mathbb{N}_+$ is the total estimated number of rhinos in year $y - 1$, and $n_y \in \mathbb{N}_+$ is the total estimated number of rhinos in year y.

The effort per poaching incident (viz., mean moved distance by poachers; Fig. 2A) was then calculated as

$$\frac{\sum_{i=0}^{p-1} \frac{A_t}{2r\left(n_{y-1} + i\frac{n_y - n_{y-1}}{p} + 1 \right)}}{p}$$

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