CONSERVATION

Dehorning reduces rhino poaching

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Across 11 southern African reserves protecting the world's largest rhino population, we documented the poaching of 1985 rhinos (2017–2023, ~6.5% of the population annually) despite approximately USD 74 million spent on antipoaching. Most investment focused on reactive law enforcement—rangers, tracking dogs, access controls, and detection cameras—which helped achieve >700 poacher arrests. Yet we found no statistical evidence that these interventions reduced poaching (horn demand, wealth inequality, embedded criminal syndicates, and corruption likely combine to drive even high-risk poaching). By contrast, reducing poacher reward through dehorning (2284 rhinos across eight reserves) achieved large (~78%) and abrupt reductions in poaching using 1.2% of the budget. Some poaching of dehorned rhinos continued because poachers targeted horn stumps and regrowth, signaling the need for regular dehorning alongside judicious use of law enforcement.

Despite decades of conservation efforts, poaching for international trade continues to threaten the existence of the world's five rhinoceros species (*1*, *2*) while also reducing tourism revenues (*3*), entrenching criminal syndicates (*4*), threatening ecosystem function (*5*), and leading to loss of human life due to violent contacts between rangers and poachers (*6*). In the Greater Kruger ecosystem of southern Africa [a critical global stronghold that protected 27% of all of Africa's rhinos in 2017; (*2*)], we documented the poaching of 1985 rhinos between 2017 and 2023 (Fig. 1). This has rapidly reduced both black rhino (*Diceros bicornis*) and white rhino (*Ceratotherium simum*) populations (*1*, *7*, *8*). Poaching has persisted despite the investment of approximately USD 74 million in diverse antipoaching interventions (Figs. 2 and 3B). Political instability, local poverty, police criminality, an ineffective justice system (with poachers often let out on bail), and involvement of conservation staff with criminal syndicates have enabled wildlife crime to thrive in the region (*4*, *9*).

Rethinking strategies to tackle the poaching of high-value wildlife

In his seminal work in the 1950s, Becker argued that crime can be reduced by increasing the probability (e.g., more police patrols) or the severity (e.g., longer prison sentences) of punishment (*10*). Researchers of wildlife poaching and trade have since applied this thinking to model poacher behavior as a function of both the risks and the costs and benefits of poaching behavior (*11*, *12*). Further evidence in behavioral economics suggests that the certainty of the cost or benefit has a strong influence on human decision-making in general (*13*, *14*).

Globally, as in our study area, efforts to combat the illegal wildlife trade have for decades focused on increasing the risk of incurring a penalty, through law enforcement measures such as militarized ranger patrols and advanced surveillance technologies [(*15*–*17*); Fig. 2]. Yet consumer demand and local poverty create financial incentives for poaching despite high risk (*9*, *18*, *19*). Also, corruption allows criminal poaching syndicates to circumvent detection and arrest through inside information on ranger and camera deployments [(*4*, *20*); Fig. 2]. Furthermore, ineffective criminal justice systems dampen the deterrence value of the penalty because sentences are seldom swift, fair, and certain (*21*). Finally, raising the likelihood of detecting and arresting poachers—through measures such as additional cameras, rangers, helicopters, and dogs—may be prohibitively expensive to implement at a scale and intensity large enough to substantially deter poacher behavior across vast wildlife areas like those analyzed in our study [(*10*, *12*); Fig. 3D]. In summary, the overall expected cost to poachers (risk times penalty) achievable through law enforcement is hindered by several contingencies and extenuating factors and is therefore often too low to substantially deter poaching.

Given these complexities, rhino custodians across Africa and Asia are increasingly turning to proactive dehorning of rhinos as an entirely different approach to poaching deterrence: reducing rewards. The staggered implementation of dehorning across eight of our study reserves and over 7 years (2284 rhinos dehorned) has provided a distinctive opportunity to empirically evaluate the effectiveness of this approach. Based on the theoretical work and contextual factors referenced above, we predicted that the large, direct, and unambiguous reduction in expected reward created by dehorning would exert a stronger influence on poacher behavior in our study area than the less direct, less certain, and more contingent increases in expected penalty achievable through law enforcement interventions (Fig. 2).

Evaluating the effectiveness of antipoaching interventions

We used quarterly data collected over 7 years (2017–2023) from 11 wildlife reserves in the Greater Kruger ecosystem to measure the effectiveness of rhino dehorning alongside traditional law enforcement interventions (antipoaching rangers, fences, security control rooms, tracking dogs, detection cameras, and others; see Fig. 2). Our unit of analysis was the poaching rate and intervention intensity per reserve per year quarter (Fig. 1). Data were combined for black and white rhino species (black rhinos constituted ~8% of the total rhino population, and poaching and dehorning rates were similar by species). The interventions were applied as part of ongoing management rather than a controlled experiment. To reduce uncertainty in the attribution of changes in poaching to specific interventions in a complex system without experimental controls, we took an interdisciplinary approach that combined correlative and quasi-experimental quantitative models with structured qualitative attribution methods from policy program evaluation (*22*, *23*).

First, we built a baseline all-intervention model to test for empirical associations between poaching rates and the intensity of implementation of 11 antipoaching interventions (Fig. 1B). We used process tracing (through interviews with reserve managers and intervention experts) to map out the causal pathways for each intervention and then tested these against our quantitative data (Fig. 2 and fig. S1). We used a

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Our approach: In our baseline all-intervention model, we tested for empirical associations between poaching rates and 11 anti-poaching interventions across 11 reserves and over 5 years (2017-2021). We then conducted a dehorning-focused quasi-experimental regression discontinuity analysis to test for any abrupt changes in poaching in response to dehorning, using a wider period of data (2017-2023).

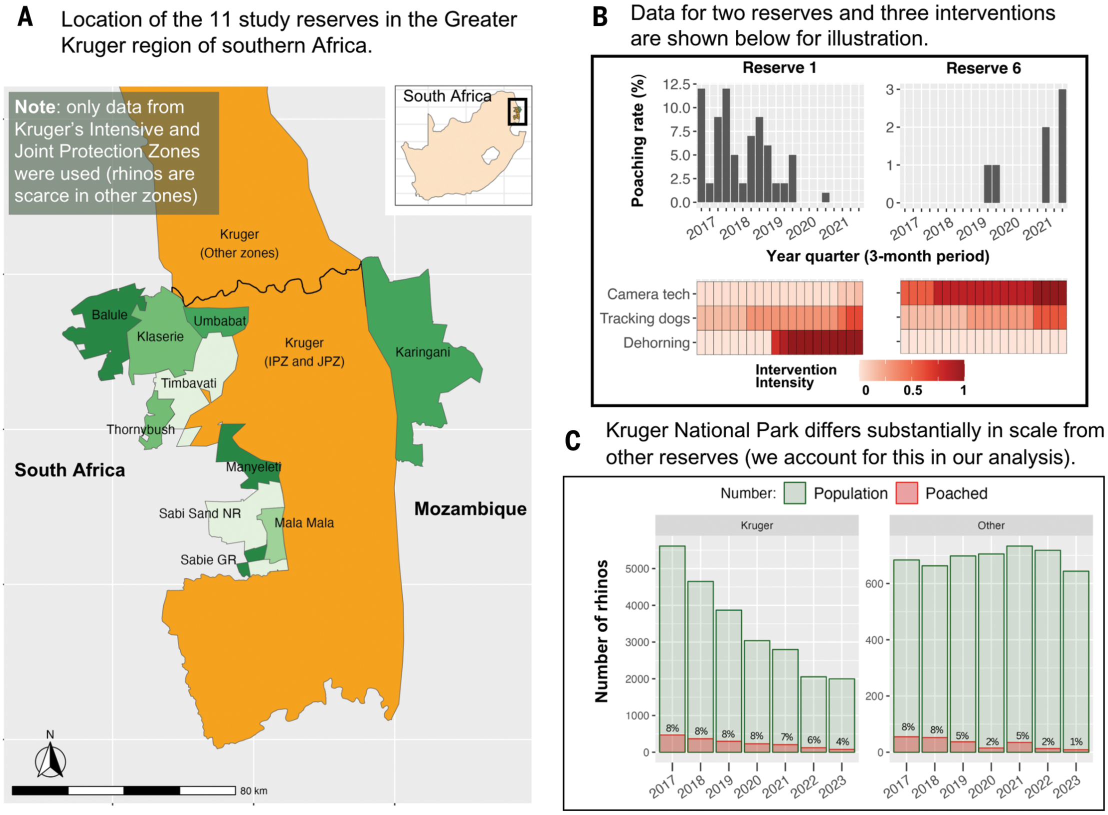

Fig. 1. Overview of study area and analysis. (**A**) We collated detailed quarterly data on poaching and interventions for 11 reserves from 2017 to 2021 (shades of green are used to distinguish the reserves visually). For Kruger NP (orange), we included data from the Intensive and Joint Protection Zones, outside of which rhinos are scarce (IPZ and JPZ, respectively). The system has outer fences, but there is free movement of rhinos between reserves. The state manages Kruger NP and Manyeleti Game Reserve (GR), whereas the other nine reserves are privately managed. Mozambique borders Kruger NP in the east. Given the distinctive size and context of Kruger NP, we conducted analyses with and without Kruger NP (see materials and methods). NR, Nature Reserve. (**B**) Poaching rates and the intensity of interventions varied across the reserves. (**C**) Kruger NP experienced large rhino population declines over the study period in contrast to stable populations on aggregate in the other 10 reserves, despite similar poaching levels in earlier years.

hierarchical Bayesian regression model with reserve and year random effects and model selection performed through regularization to account for multiple testing (see materials and methods). Next, we quantified evidence for intermediate steps along hypothesized pathways, such as the number of poachers arrested using tracking dogs. Finally, we used contribution analysis through structured results workshops to further appraise the empirical support for intervention pathways and to interrogate how and under which conditions interventions worked or did not work as intended (*23*). See materials and methods for full details.

Second, we built a dehorning-focused model to strengthen causal inference for our main intervention of interest. Although several tests confirmed no significant temporal or spatial autocorrelation in our all-intervention model residuals (figs. S3 to S8), this model was limited by the nonrandom application of multiple interventions that overlapped inconsistently in space and time. By contrast, seven reserves implemented dehorning abruptly (dehorning almost all rhinos present within 1 to 2 months; fig. S11) and in a staggered fashion (two reserves in early 2019, two in late 2019, and three in mid-2022). This provided good spatial and temporal contrast, allowing us to conduct a quasi-experimental regression discontinuity in time analysis to test for abrupt changes in poaching in response to dehorning (*24*–*26*). Staggering of dehorning by site provided multiple replicates of potential discontinuity, helping us to separate dehorning effects from potential confounders [as in (*25*)]. To account for pre-dehorning trends in poaching, our model included terms to measure immediate changes in poaching related to dehorning, as well as any change in the average poaching trend [see (*26*) and Fig. 4B]. We also confirmed that none of the other interventions changed abruptly around the point of dehorning (fig. S9).

Finally, we computed the relative risk of poaching faced by dehorned versus horned individuals at the landscape level and individual rhino level, as well as an estimate of the cost per rhino saved from poaching (see materials and methods and Fig. 5). Dehorning was conducted by a specialized veterinarian and an operational team and involved sedation of the rhino and painless removal of both horns above the growth plate using a chainsaw, followed by an antidote to sedation. Maintenance dehorning was carried out such that all rhinos were repeatedly dehorned at ~18-month intervals, owing to the rate of horn regrowth (fig. S11). Research, though nascent, suggests limited effects of dehorning on rhino ecology, behavior, and reproduction (*27*–*30*).

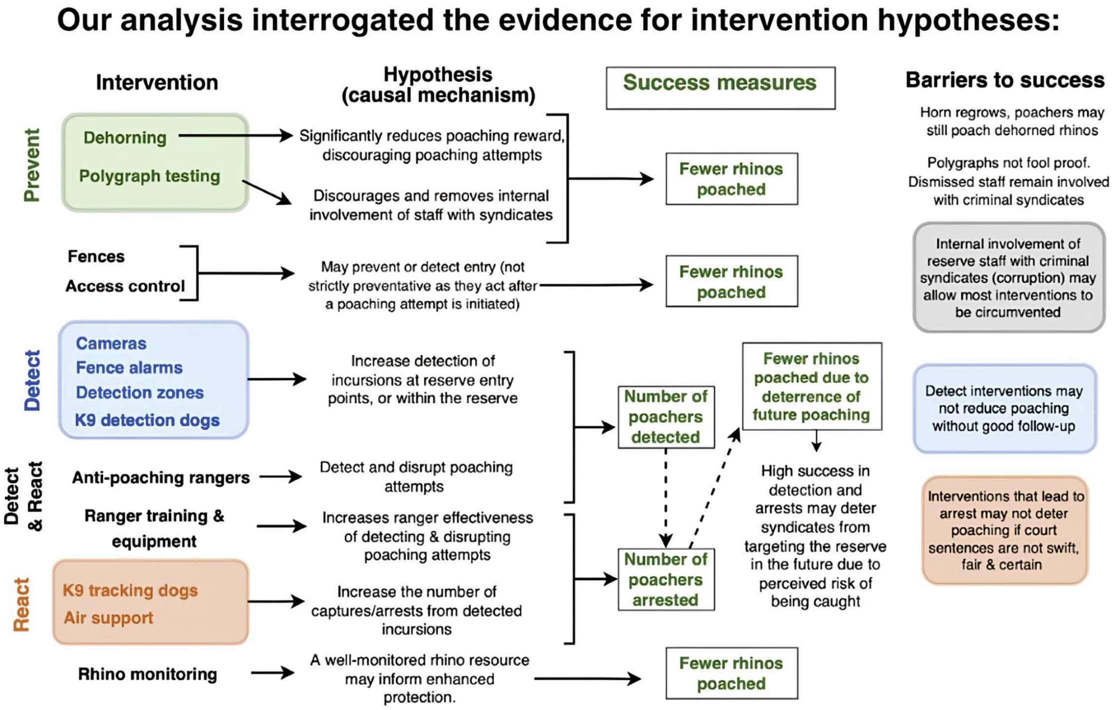

Fig. 2. Hypothesized causal pathways as to how the different categories of interventions act to reduce rhino poaching, including potential barriers to success. This conceptual model was developed from workshops and interviews with reserve managers and other experts. The statistical model served to test the strength of evidence for these hypotheses. Interventions were classed into three groups based on their approach: (i) "Preventative interventions" are designed to stop poaching incursions before they happen, (ii) "detect interventions" are designed to detect poacher incursions into a reserve, and (iii) "react interventions" are designed to react to detected incursions and help track, capture, and arrest poachers.

Results

Intervention implementation and cost

Across the 11 Greater Kruger reserves between 2017 and 2023, the horns of 2284 rhinos were proactively removed (dehorning), 671 cameras of seven different types were installed to detect poachers, 5562 polygraph tests were conducted (with 129 staff dismissed after the failure of a test), 45 detection dogs were deployed at reserve access points, 47 tracking dogs were deployed within reserves, 1150 km of detection zones were maintained and checked (roads or rivers checked for poacher footprints), and more than 500 antipoaching rangers were deployed at any given time.

To illustrate the complex environment in which interventions are implemented, and the strategies used by poachers to circumvent them, see box S1 in the supplementary materials for a description of how several interventions acted in concert to achieve the arrest of a core member of a poaching syndicate. An estimated minimum of USD 74 million (using the mid-2019 spot rate of ZAR 14.4 to USD 1) was spent on interventions related to rhino protection across all reserves in the period 2017–2021 (Fig. 3D; cost data were not available for 2022 and 2023). This equated to an estimated USD 3120 spent per resident rhino per year. Across all reserves and years, higher total expenditure on interventions was weakly correlated with lower poaching rates (fig. S20).

Dehorning was associated with large and abrupt reductions in poaching

In our baseline all-intervention model, we found strong statistical evidence that dehorning reduced poaching (Fig. 3). On average, dehorning all rhinos present on a reserve reduced poaching by ~75% from pre-dehorning levels (95% credible interval: 57 to 87% reduction), having accounted for other interventions and random effects (Fig. 3B). Poacher incursions were also significantly lower after dehorning (fig. S24), supporting the hypothesis that poachers make fewer attempts to enter reserves with dehorned rhinos because of the perception of a substantially reduced reward from poaching (Fig. 2 and fig. S1). Conclusions were the same (no significant intervention effects apart from dehorning) for supplementary models with flat Bayesian priors (fig. S2), excluding Kruger National Park (NP) data (fig. S26), using the raw number of rhinos poached instead of the poaching rate (fig. S27), using bias-corrected population estimates (fig. S28), including combinations of intervention variables (fig. S29), and including lagged intervention effects (fig. S30).

For the seven reserves that implemented abrupt dehorning, we found strong evidence for a simultaneous and abrupt reduction in poaching as well as a change in the poaching trend (Fig. 4; Bayesian regression discontinuity effects exclude zero; table S1). The estimated reduction in poaching for the regression discontinuity model was 78% (95% credible interval: 38 to 92%; table S1). Given the different times at which dehorning was introduced on each reserve (two in early 2019, two in late 2019, and three in mid-2022), it is unlikely that some unmeasured factor could have explained these effects (*29*). Furthermore, any abrupt change in the other interventions around the dehorning event was ruled out as a possible explanation for the abrupt change in poaching (fig. S9).

Using data across all reserves and years, we estimated a 13% risk of an individual horned rhino being poached in a particular year compared with a 0.6% poaching risk for a dehorned rhino, which represents a 95% reduction in relative poaching risk (Fig. 5A). Risk was also reduced at the landscape level, with higher annual levels of dehorning at this level (all 11 reserves) associated with reduced poaching rates overall (Fig. 5B and fig. S22). Thus, although dehorning on one reserve may have displaced poaching pressure to others, overall poaching rates in the system did decline. By making several simplifying assumptions,

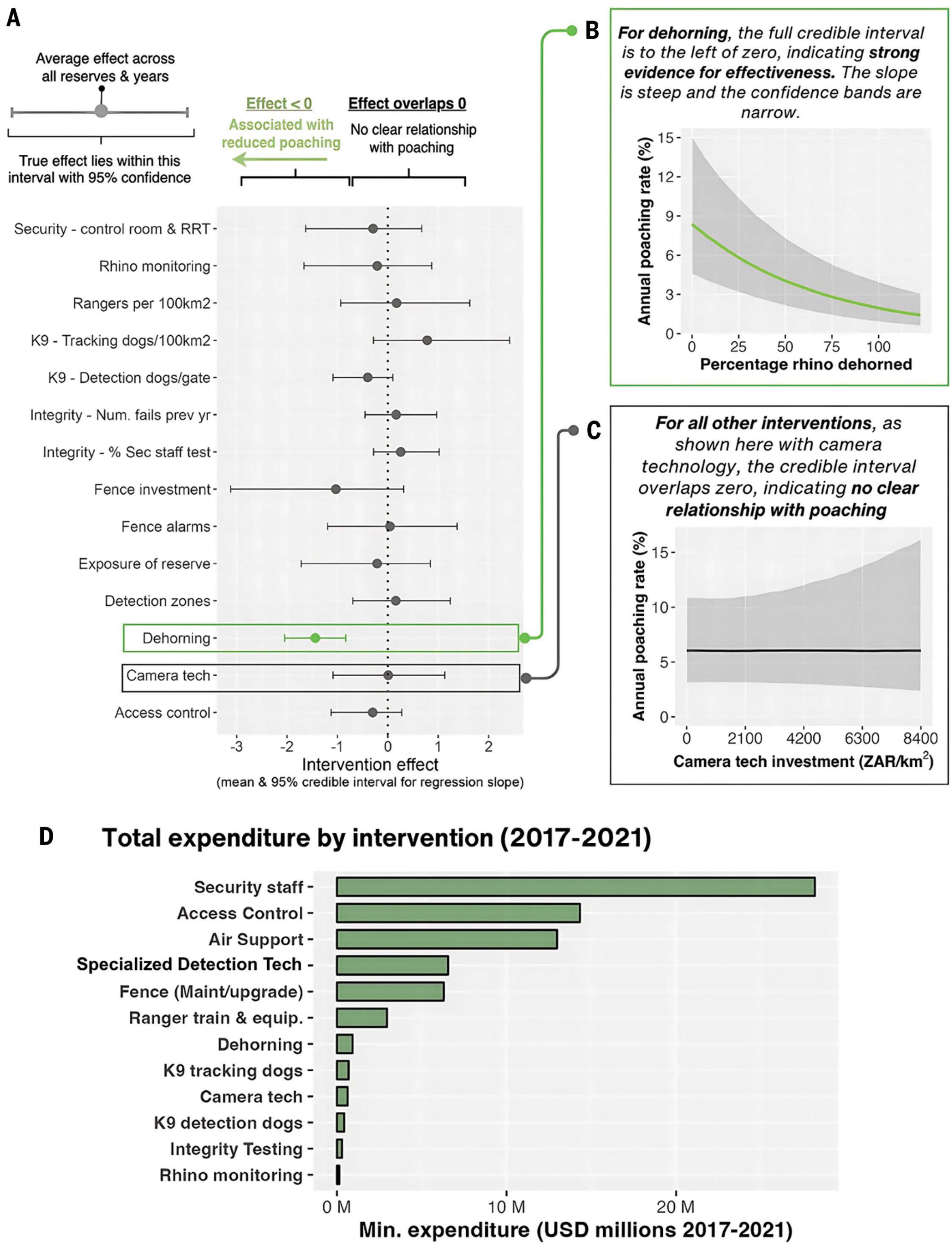

Fig. 3. The effectiveness and cost of antipoaching interventions. (**A**) Effectiveness was measured as the slope of the relationship between the intensity of each intervention and the poaching rate in a statistical model that included all interventions together and with random effects to account for unmeasured confounding factors (see materials and methods). All intervention indices are standardized to the 0 to 1 scale to allow direct comparison. Some intervention indices were correlated, so the effects of ranger training and equipment and tracking technology are shown in fig. S25. RRT, rapid response team. (**B** and **C**) Conditional effects plots for the effect of dehorning and camera technology, respectively, having accounted for all other interventions and random effects. (**D**) Total expenditure by intervention.

we estimate that a total of between 70 and 134 rhinos were saved from poaching in the 12 months after dehorning across the eight implementing reserves, at a median cost of USD 7133 per rhino saved (table S2). Dehorning was also the most cost-efficient intervention (USD 570 per rhino operation), using ~1.2% of the USD 74 million total expenditure to achieve large reductions in poaching (Fig. 3 and figs. S20 and S21).

Despite these strong effects, we recorded the poaching of 111 previously dehorned rhinos, 107 of which were poached within Kruger NP in 2022–2023 (fig. S23). During these 2 years, only 50 to 55% of rhinos on Kruger had been dehorned in the previous 18 months, on average, and horned and dehorned rhinos were poached at similar rates (fig. S23). Evidently, although the overall poaching rate within Kruger NP decreased from 7.5 to 3.4% after dehorning (see reserve 3 in Fig. 4), criminal syndicates remained willing to poach dehorned rhinos there at fairly high rates. A sizable proportion of horn mass remains on the rhino after dehorning, as veterinarians are only able to cut the horn up to the

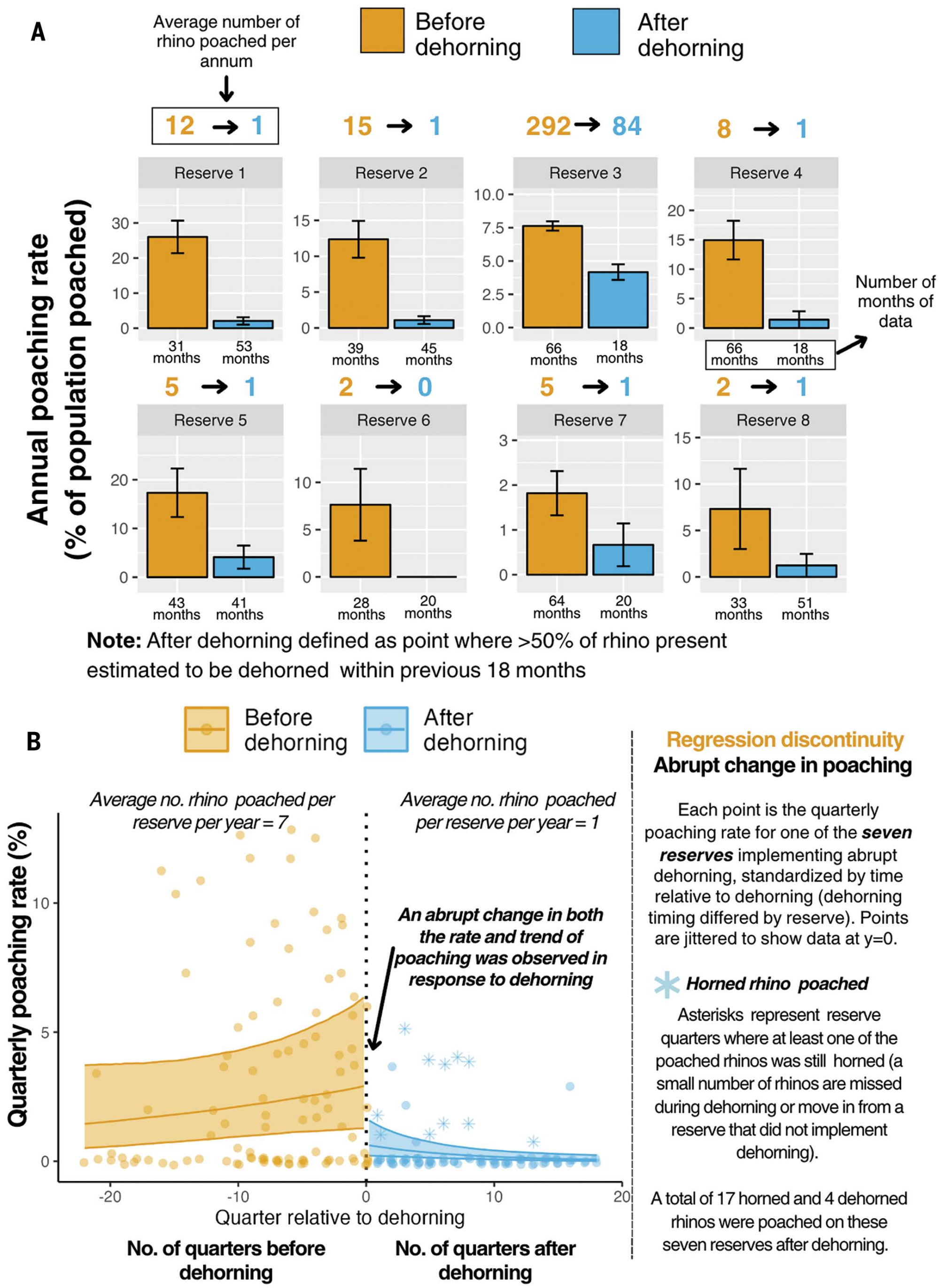

Fig. 4. Dehorning is associated with abrupt and significant reductions in poaching. (**A**) Annual poaching rates before and after dehorning for the eight reserves that implemented dehorning (mean ± SE). All these reserves implemented abrupt dehorning except Kruger NP (reserve 3). (**B**) Rhino poaching rates before and after dehorning, with data from the seven reserves that implemented abrupt dehorning standardized by the year quarter relative to dehorning (dehorning was staggered across these reserves between 2019 and 2022; see materials and methods). The blue asterisks indicate that at least one of the rhinos poached on a particular reserve in a particular quarter was still horned (either missed during dehorning or had moved in from a reserve that had not dehorned its rhinos). Trend lines and discontinuity estimates are from the Bayesian regression discontinuity-in-time model that tested for an immediate dehorning effect as well as a change in the poaching trend (see materials and methods and table S1).

growth plate, leaving 5 to 15 cm of basal horn length behind depending on the rhino's age (data are from field measurements during dehorning operations). The specific targeting of Kruger NP might be explained by lower coverage and frequency of dehorning (fig. S23) and the comparatively easy access to the reserve from Mozambique, where poaching syndicates may be more willing to poach dehorned rhinos and less able to shift operations elsewhere (compared with South African syndicates). The effective rate and frequency of dehorning was also lower in Kruger NP (fig. S23).

Law enforcement interventions show less direct success

Apart from dehorning, the credible intervals for the effects of the other 10 interventions overlapped zero, suggesting that the greater intensity of these interventions was not associated with any significant change in poaching across the study (Fig. 3, A and C). However, these results do not necessarily imply that the other interventions were ineffective. The credible intervals for all interventions are plausibly consistent with a positive effect, and the inconclusive results may reflect a low power to detect impacts from a real-world, data-sparse system in which interventions were implemented in a nonexperimental way that did follow a strong experimental design. Many interventions were successful on their own terms, as they were associated with increased rates of poacher detection and arrest, sometimes before the poaching event (fig. S31), even if this did not, on aggregate, translate to a significant effect across reserves. Detection cameras equipped with artificial intelligence detected numerous poachers, tracking dogs and air support helped track and arrest several hundred poachers, and polygraph testing led to the dismissal of 129 staff members after test failures suggested collusion with criminal syndicates (fig. S31).

Discussion

Our results bring into sharp focus the limitations of reactive approaches to rhino poaching when poachers have already entered reserves. Interventions that work to aid poacher detection and arrest, although a necessary element of the antipoaching toolkit, are compromised by several systemic factors that may dampen their effectiveness (Fig. 2). First, ongoing socioeconomic inequality incentivizes a large pool of vulnerable and motivated people to join, or poach for, criminal syndicates even when the risks are high (*4*, *9*). Second, entrenched corruption (among police and reserve staff and in the courts) allows offenders to circumvent many antipoaching efforts, greatly compromising their deterrent value (*18*, *20*). Third, ineffective criminal justice systems mean that

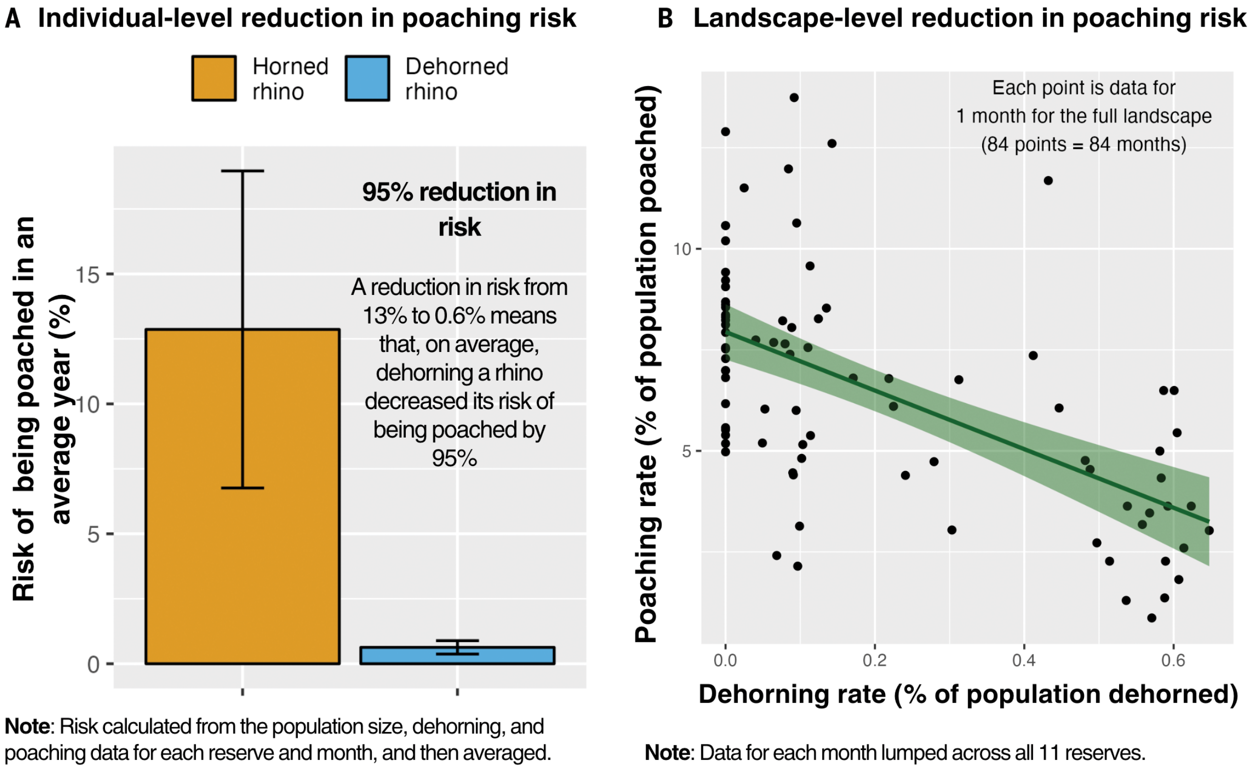

Fig. 5. Individual rhino and landscape-level reductions in poaching risk after dehorning. (**A**) Risk ratios for dehorning effectiveness. Risk ratios compare the poaching rate of horned rhino to that of dehorned rhino, using data across all reserves and months (see materials and methods). Error bars represent mean + SD. (**B**) The relationship between the monthly poaching and dehorning rate across 2017–2023 (84 months; data lumped across reserves). The shaded region represents the 95% confidence interval for the smoothed regression line.

arrested offenders often escape punishment, with evidence from our study area of multiple repeat offenders (*4*). The fact that these conditions are by no means specific to our study area broadens the importance of our work (*31*, *32*).

Reactive approaches also raise inevitable human rights concerns, as apprehending armed poachers in the field carries a high risk of either rangers or poachers losing their lives (*33*). Addressing the socioeconomic vulnerability of local communities, which allow syndicates to access a pool of poachers, is another critical strategic priority [requiring long-term collaborative efforts by government, civil society, and the private sector; (*30*)].

Dehorning was the only intervention for which we found strong evidence for effectiveness. Interventions that unambiguously reduce the revenues from poaching (such as dehorning) may be more robust to contextual complexity than interventions that act through actual or perceived costs and risks of poaching [(*9*, *12*–*14*, *20*); also see Fig. 2]. Our results align with work in behavioral economics that suggests that people respond more to outcomes that are more certain (a clear and substantial reduction in reward, such as through dehorning) than to those that are less certain (poacher detection, arrest, and sentencing are all subject to high uncertainty) (*13*, *14*). Dehorning is also an example of a more general approach in situational crime prevention—that of reducing opportunities for crime by rendering it less rewarding, an approach with many analogs in the prevention of more traditional crimes (*34*, *35*). Another likely reason for the effectiveness of dehorning is that it is less easily thwarted by internal corruption. Whereas cameras, dogs, and rangers can be avoided by poachers with internal information, dehorning cannot.

Although the removal of valuable body parts to reduce poaching is often not possible for other species threatened by the illegal wildlife trade, the broader approach of reducing opportunities for and rewards from poaching (as opposed to increasing risk) is generalizable. Researchers in Venezuela, for example, found that removing parrot nestlings from nests into safer areas at night and returning them in the morning led to large reductions in poaching (*36*). In Cape Town, South Africa, conservationists paint indigenous trees to discourage illegal debarking for medicinal trade (*37*).

Our results make a strong case for dehorning as a strategy to reduce poaching, yet there are several caveats. First, dehorned rhinos were occasionally poached (particularly those with substantial regrowth). Second, dehorning in the Greater Kruger may have displaced poaching pressure to horned populations elsewhere [with some evidence of a shift to the second largest stronghold for South African rhinos, namely, Hluhluwe-iMfolozi Park; (*38*)]. It remains to be seen whether dehorning would be as effective in the absence of horned populations that are accessible elsewhere to criminal syndicates. If dehorning had taken place in the total absence of other interventions, poaching for the stumps and regrowth would probably have continued given the lack of risk to poachers. It follows that the effective implementation of a suite of other interventions is probably necessary to ensure the ongoing effectiveness of dehorning, whether in our study system or elsewhere. Finally, the effects of dehorning on rhino biology are still unclear, with present research suggesting that dehorning may alter rhino space use but not survival and reproduction (*27*–*30*).

Our results present a challenge to governments, funders, the private sector, and nongovernmental organizations to reassess their strategic approaches to wildlife crime in general and rhino poaching in particular. Although detecting and arresting poachers is essential, strategies that focus on reducing opportunities for and rewards from poaching may be more effective. Demand reduction, by reducing the price of wildlife products, is one such strategy (*39*). Similarly, efforts to support the socioeconomic resilience of local people may help create viable economic alternatives that render rewards from poaching less attractive (*40*). For practice and policy in global rhino conservation, our work makes a strong case for dehorning as a tool that may achieve large and immediate reductions in poaching in cases where law enforcement has not yielded the desired level of poacher deterrence. Yet the fact that poaching of dehorned rhinos continued at fairly high rates in Kruger NP suggests that horn stumps and regrowth remain attractive to criminal syndicates, pointing to the need for regular dehorning and ongoing prudent use of law enforcement.

Finally, our work is an example of both the value and difficulty of impact evaluation in conservation science and practice. We demonstrate how combining multiple lines of evidence (qualitative attribution methods through workshops and interviews, tailored statistical models, and quasi-experimental approaches) can help reduce uncertainty in the attribution of biodiversity outcomes to specific policies or interventions in messy contexts. Our work is also an example of a situation in which conservation practitioners reached out to scientists for support in addressing a perceived problem, rather than the scientists coming to an area with a question that may or may not be one of interest to local practitioners. This flipping of the scientist-practitioner relationship and the direction of knowledge exchange is still unusual [but see (*41*) for another example]. Where possible, to maximize future learning and adaptation, we suggest that scientists and conservation practitioners codesign research that seeks to actively evaluate interventions in a more explicitly experimental way, the lack of which was a limitation of this study.

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SUPPLEMENTARY MATERIALS

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Materials and Methods; Figs. S1 to S31; Tables S1 to S3; Box S1; References (*43*–*55*); MDAR Reproducibility Checklist

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