Effects of integrated conservation–development projects on unauthorized resource use in Volcanoes National Park, Rwanda: a mixed-methods spatio-temporal approach

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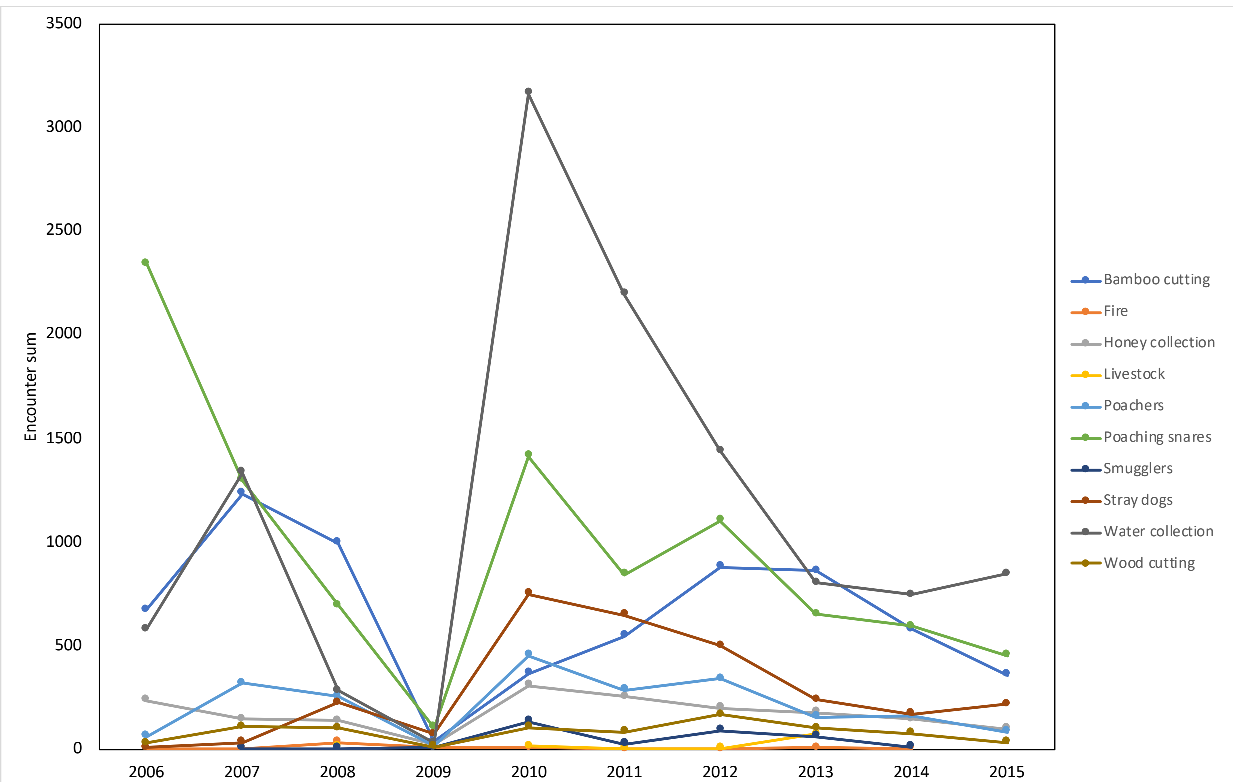
SUPPLEMENTARY TABLE 1 Summary statistics for all variables used.

	Variable	Description	Obs.	Mean	SD.	Min	Max	Source
Interest	*illegal*	Raw RBM-URU data 2006-2015 aggregated to sector	108	320.7315	413.0114	0	2165	(Sabuhoro; RDB-RMW)
	cpue δ	RBM-URU corrected for effort using ranger count and coverage	108	184.2392	240.409	0	1341.434	(Sabuhoro; RDB-LEW) Calculated in Stata
	trs	TRS funding to each sector USD 2005-2015	120	9825.63	10309.91	0	72000	(Sabuhoro; RDB)
	ngo	CNGO and PS USD funding 2005-2010 and 2011-2015 periods/ sector	120	69285.98	105848.8	0	378000	(Sabuhoro; RDB)
	totalinvest	Sum of TRS and NGO in USD/sector/year	120	79111.61	107834.7	0	405203.8	Calculated in Stata
Control	*popdens*	Density by cell/sector (people/km^2)	120	705.3699	153.2096	378.4872	1012.008	AidData Geoquery
	area_wiVNP	Area of sector within the VNP park boundary (km^2)	120	13.65461	10.75092	.2097713	30.90492	Calculated in ArcGIS
	precip	Annual mean precipitation (mm) for sector	120	105.9179	12.03023	85.44167	137.07	AidData Geoquery
Spatial	*wtotalinvest*	Spatial lag of *totalinvest*	120	80663.33	52037.68	28004.69	188022.8	Calculated in GeoDa
	wprecip	Spatial lag of *precip*	120	105.5763	6.619105	97.30417	114.3207	Calculated in GeoDa
	wpopdens	Spatial lag of *popdens*	120	687.5067	90.14298	557.4353	827.0884	Calculated in GeoDa
	wtrs	Spatial lag of *trs*	120	10303.4	1916.006	7966.572	14447.63	Calculated in GeoDa
	wngo	Spatial lag of *ngo*	120	70005.61	51156.08	17801.15	173575.1	Calculated in GeoDa

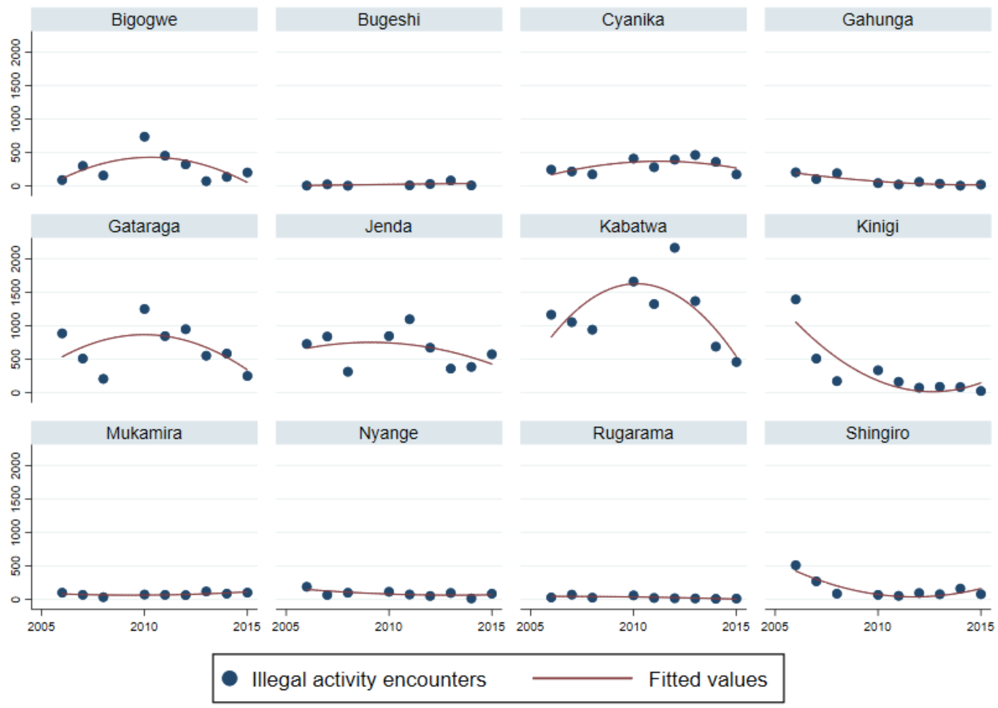
Note: RBM: Ranger-based monitoring; URU: Unauthorized resource use; RMW: Research and Monitoring Warden; LEW: Law Enforcement Warden

SUPPLEMENTARY MATERIAL 1 Data preparation.

In the ranger-based monitoring data, we dropped 2005 because observation descriptions were missing, preventing differentiation between control points, species sightings, and illegal activities encounters. We also dropped 2009 because data was lost due to a software shift that year. Thus 2009 contains very few illegal activity observations: 156 compared to approximately 2,000 observations for all other years in the 2006-2015 period (Supplementary Fig. 1; RDB-RMW, personal communication, 2018). We chose to drop rather than interpolate because policy changes in 2010 increased focus on incidents of water collection in the parks, resulting in inconsistent trends in years surrounding 2009. On this note, although the 2010 policy changes explain the increase in illegal activities recorded in 2010, 29 extreme and influential outliers (>6σ standard deviations from the mean) from that year were dropped (Hsiang and Sekar, 2016). These observations recorded greater than 70 total incidents at once, such as "200" for a water collection observation. These were perhaps data entry errors, as it is highly improbable that 200 water collectors existed in the same observation. Data was also cleaned to include only illegal activities, translated from French to English as needed, and consistently labeled (e.g., "wood cutting" vs. "trees cut," or "wire snare" vs. "poaching snare") (Supplementary Fig. 1). Supplementary Fig. 2 also presents the temporal trends in illegal activities by sector, excluding 2009, for the study period.

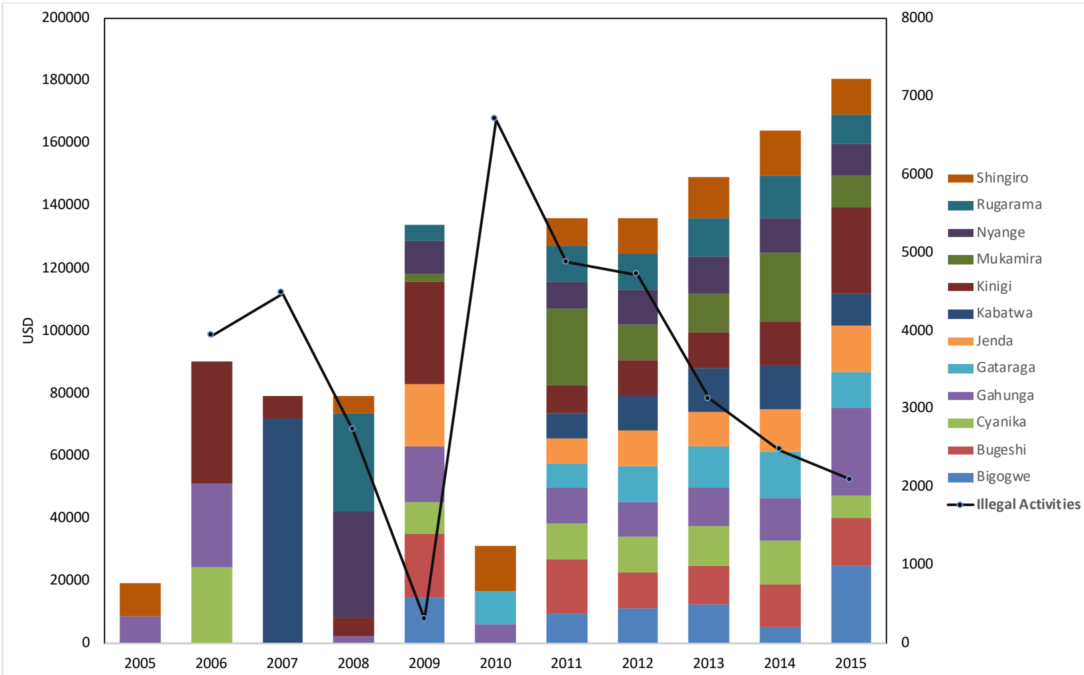


SUPPLEMENTARY FIG. 1 Types of unauthorized resource use encountered on ranger patrols by annual count. Data loss for 2009 is evident, illustrating its exclusion from analysis. Policy changes emphasized water collection in 2010. (Data; RDB-RMW, personal communication, 2018)



SUPPLEMENTARY FIG. 2 Trends in illegal activities by sector, 2009 excluded. Fitted values using two-way quadratic prediction plots. Produced in Stata. (Data: RDB-RMW, personal communication, 2018)

Similar to the ranger patrol logs, the tourism revenue sharing data for the year 2010 is inconsistent with surrounding years. Although approximately $129,000 USD was collected by revenue-sharing, bureaucratic and fiscal policy changes in 2010 resulted in distribution of only $31,200 USD. Project selection proposals were not submitted prior to national budget finalization, so only $31,200 were released. This was confirmed by multiple sources (RDB-CCW personal communication, 2018; RDB-RMW personal communication, 2018). Approximately $135,000 USD was distributed in surrounding years (Supplementary Fig. 3).



SUPPLEMENTARY FIG. 3 Combination plot. Left y-axis: Tourism revenue sharing distributed in USD, by sector annually. Right y-axis: Annual count of illegal activities. 2009 is included here but excluded in analysis. Produced in Excel. (Data: RDB-RMW, personal communication, 2018)

For analysis, we spatially joined conservation-NGO/ecotourism private sector and illegal activities points using administrative boundaries in ArcGIS. We aggregated both to sector level to accommodate the scale of the revenue-sharing data, which we then also joined to the GIS. This dataset was extracted for regression in Stata. See summary statistics in Supplementary Table 1.

Importantly, we corrected for sampling bias in the ranger-based monitoring data using catch per unit effort, as described in Eqn 1 and Eqn 2 in the main article (also below). Data used for our calculation was constrained in two ways: 1) by limited access to raw spatial data of patrol coverage and 2) by the aforementioned data management software shift in 2009.

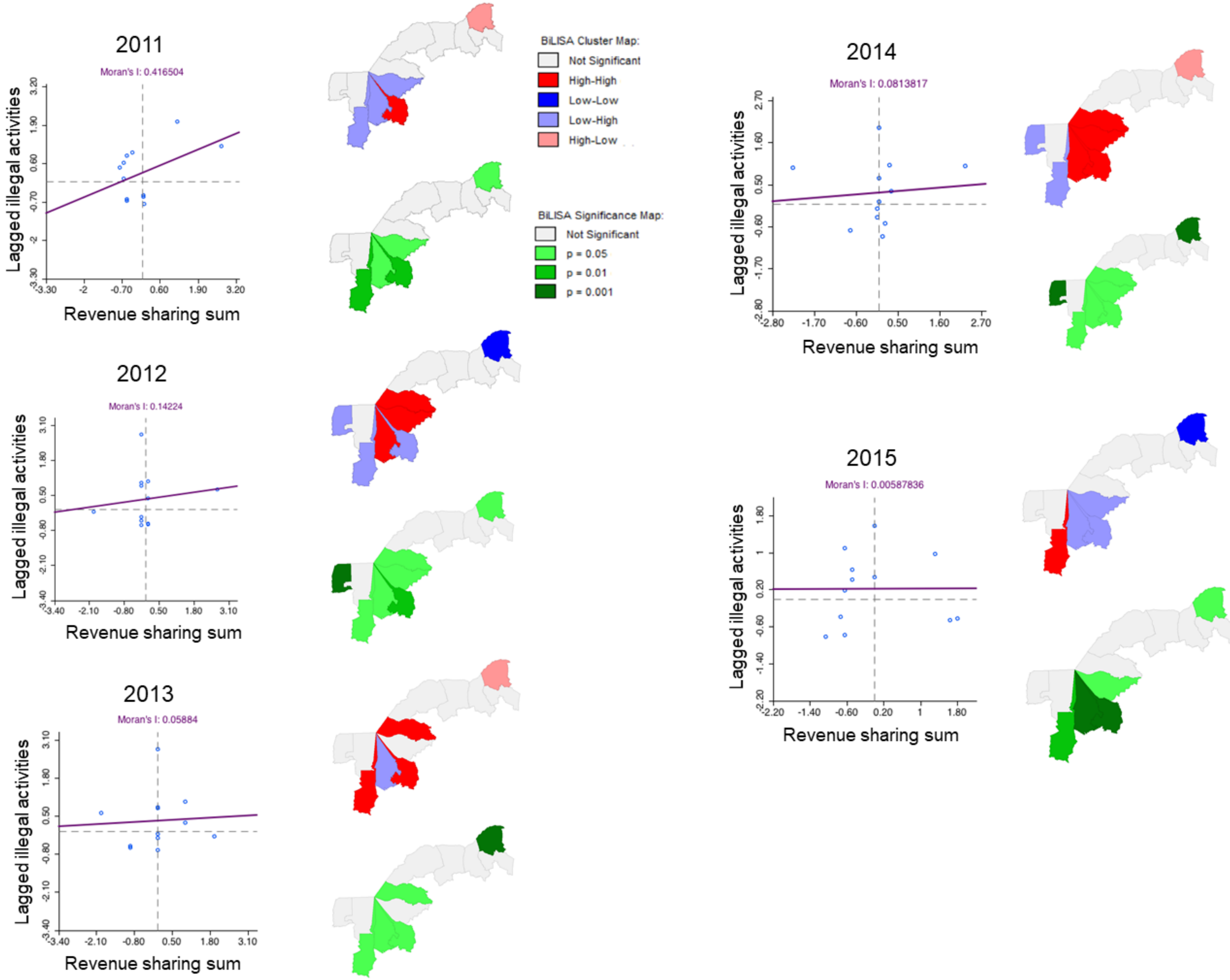
$$\delta_{st} = Encounters_{st} \times Effort_t$$

Eqn 1

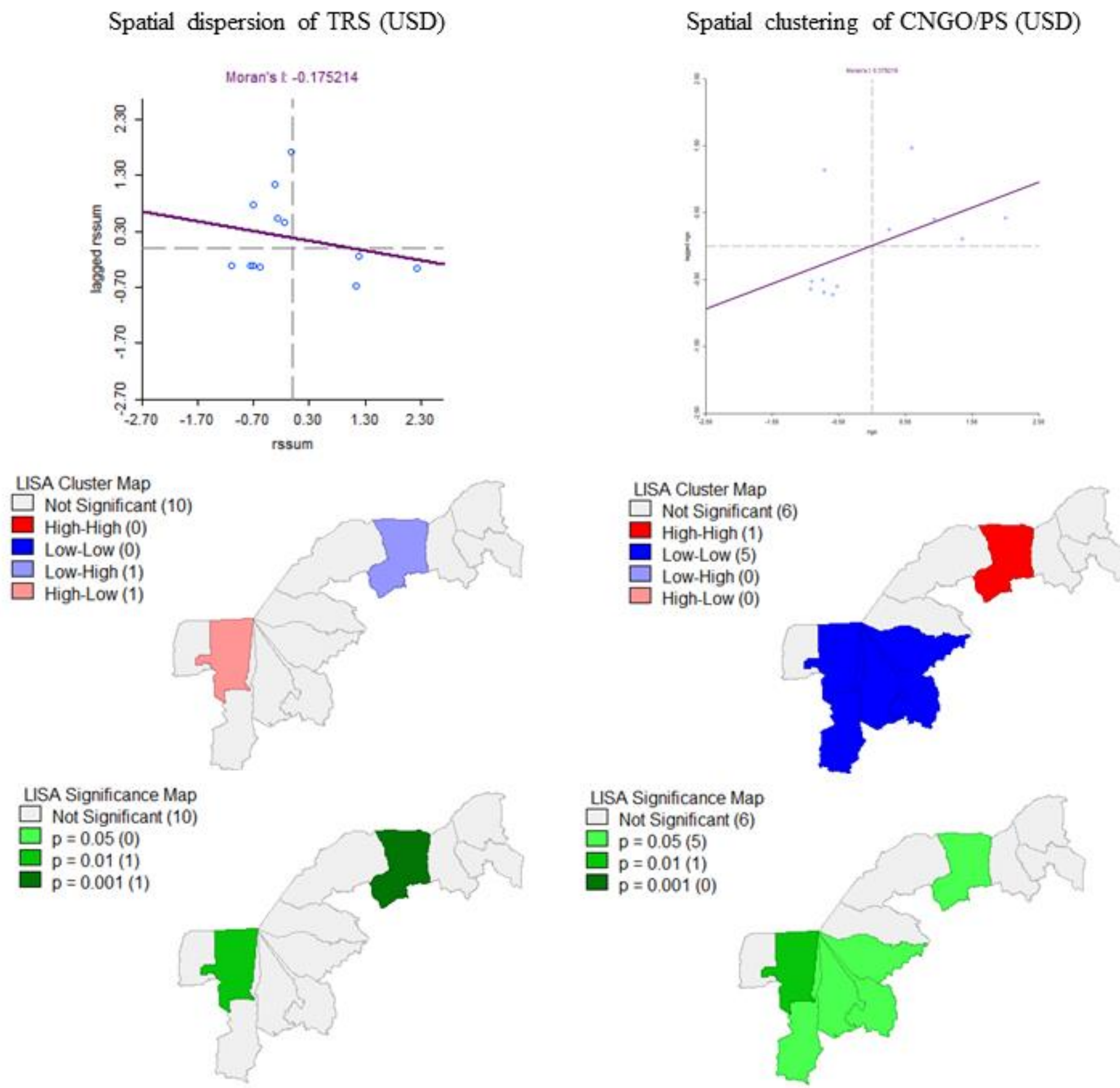
$$Effort_t = Rangers_t \times Coverage_t$$

Eqn 2

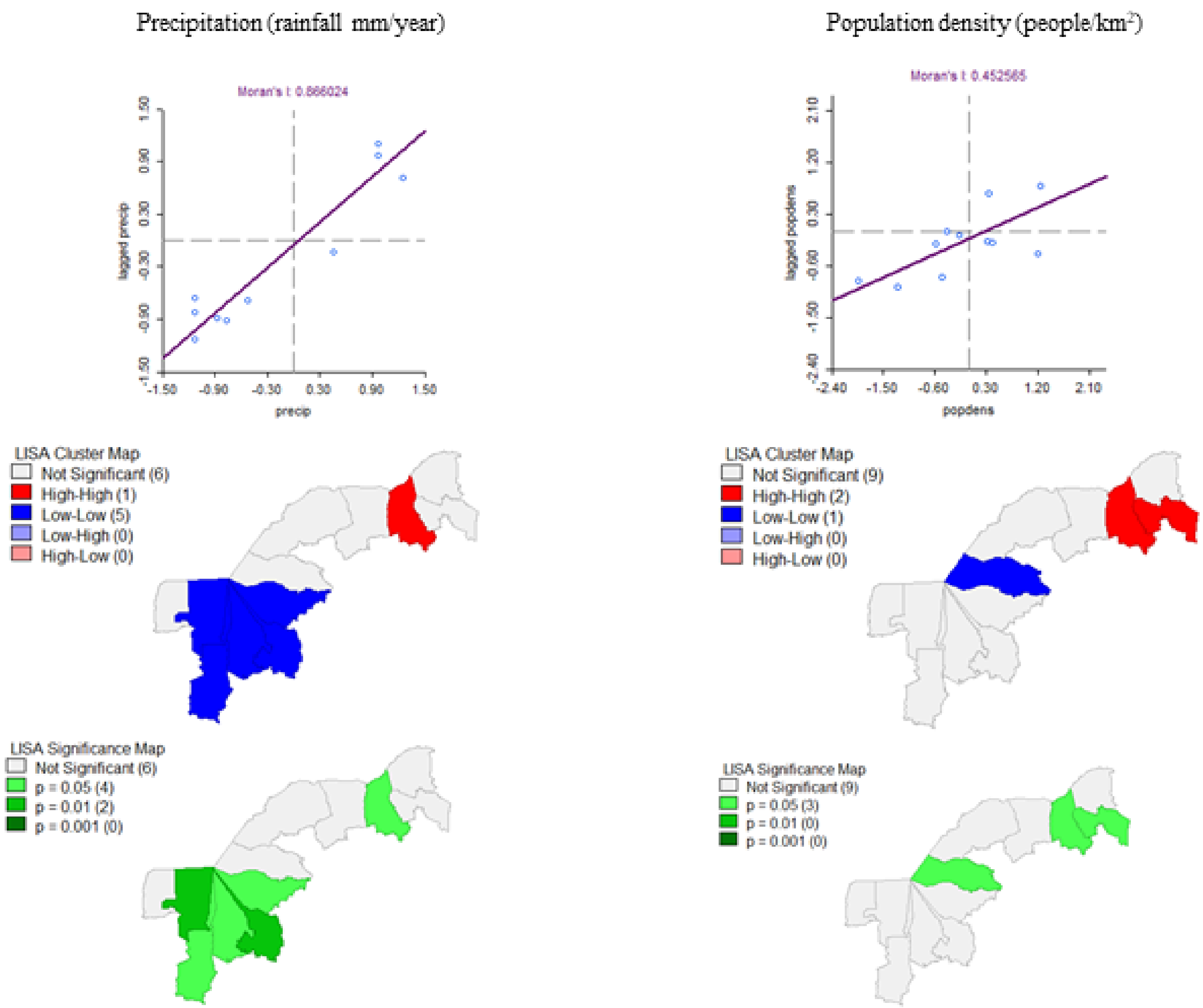
To calculate effort, we used (1) a spatially-extracted measure of annual patrol coverage and (2) annual number of rangers on patrol. First, due to the sensitive nature of the data used, two of the wardens at Volcanoes National Park used the patrol coverage data in ArcGIS to extract a proportion of park area covered annually. The raw spatial data that contains the actual path of those patrols was not made available. As such, we used this spatially extracted calculated annual statistic for proportion of park area covered by ranger patrols, which gave us the best possible approximation of annual coverage. Next, another warden additionally supplied us with aggregated annual data indicating number of rangers that joined on patrols each year. We use number of rangers on patrol rather than patrol days or number of patrols because of differences in time stamps in the raw data. The ranger-based monitoring data for 2010-2015 (after the previously-discussed 2009 software shift) contains variables in the datasets with time stamps that would enable calculation of number of patrols or patrol days annually. However, in the pre-2009 datasets, dates were inconsistently recorded, and we could not reliably calculate number of patrols or patrol days for each year. Due to this data inconsistency, we found that obtaining number of rangers patrolling from the warden's records was the best possible option for correction for patrol effort. While weighting by the number of patrols or patrol days would be ideal, we could not reliably calculate this without losing three years of observations, and effectively cutting our temporal period to six years (which, for fixed-effects regression, would have resulted in a sample of 72). Therefore, this measure of effort, combined with the spatial extraction of proportion of park coverage, while imperfect, provided us with the best possible measures of patrol effort and coverage.



SUPPLEMENTARY FIG. 4 Bivariate local Moran's I. Bivariate local Moran's *I* statistic with significance and cluster maps for 2011–2013. Plots and cluster maps show how illegal activities (*Y*) are clustered relative to sector-level tourism revenue-sharing (*X*). High-low and low-high in the bivariate local indicator of spatial association cluster maps (light red and blue), with corresponding significance tests (shades of green), indicate neighbourhoods of low illegal activity clustered with high levels of revenue-sharing and vice-versa. (Lee, 2001; Anselin, 2018).



SUPPLEMENTARY FIG. 5 Spatial autocorrelation for key variables. Univariate local Moran's I plot and cluster and significance maps for tourism revenue sharing funding and funding from conservation NGOs.



SUPPLEMENTARY FIG. 6 Spatial autocorrelation for key variables. Univariate local Moran's I plot and cluster and significance maps for precipitation and population density.

SUPPLEMENTARY MATERIAL 2 Specific analysis of water projects and water collection incidents.

To address the potential bias in the conservation-NGO project data towards water tank projects (evident in Table 1 in the main article), the direct implications that these projects should have for reducing incidents of water collection in the park, we conducted separate analyses of water projects relative to incidents of water collection: two model specifications with water projects/water incidents only; and two model specifications with all other projects/illegal incidents, excluding water (Supplementary Table 2). We found trends similar to the overall analysis in terms of the difference between revenue-sharing and conservation-NGO projects.

Notably, even with the water collection incidents/water tank projects, the difference in effect between TRS and CNGO projects remains (Supplementary Table 2, Column 1, CNGO negative and significant, TRS insignificant and positive). For water only, it appears that when uncorrected, TRS-funded water tanks have had a negative effect on water collection incidents, but the significance of this relationship is lost when illegal activities are corrected for catch per unit effort, which is not the case for CNGO projects.

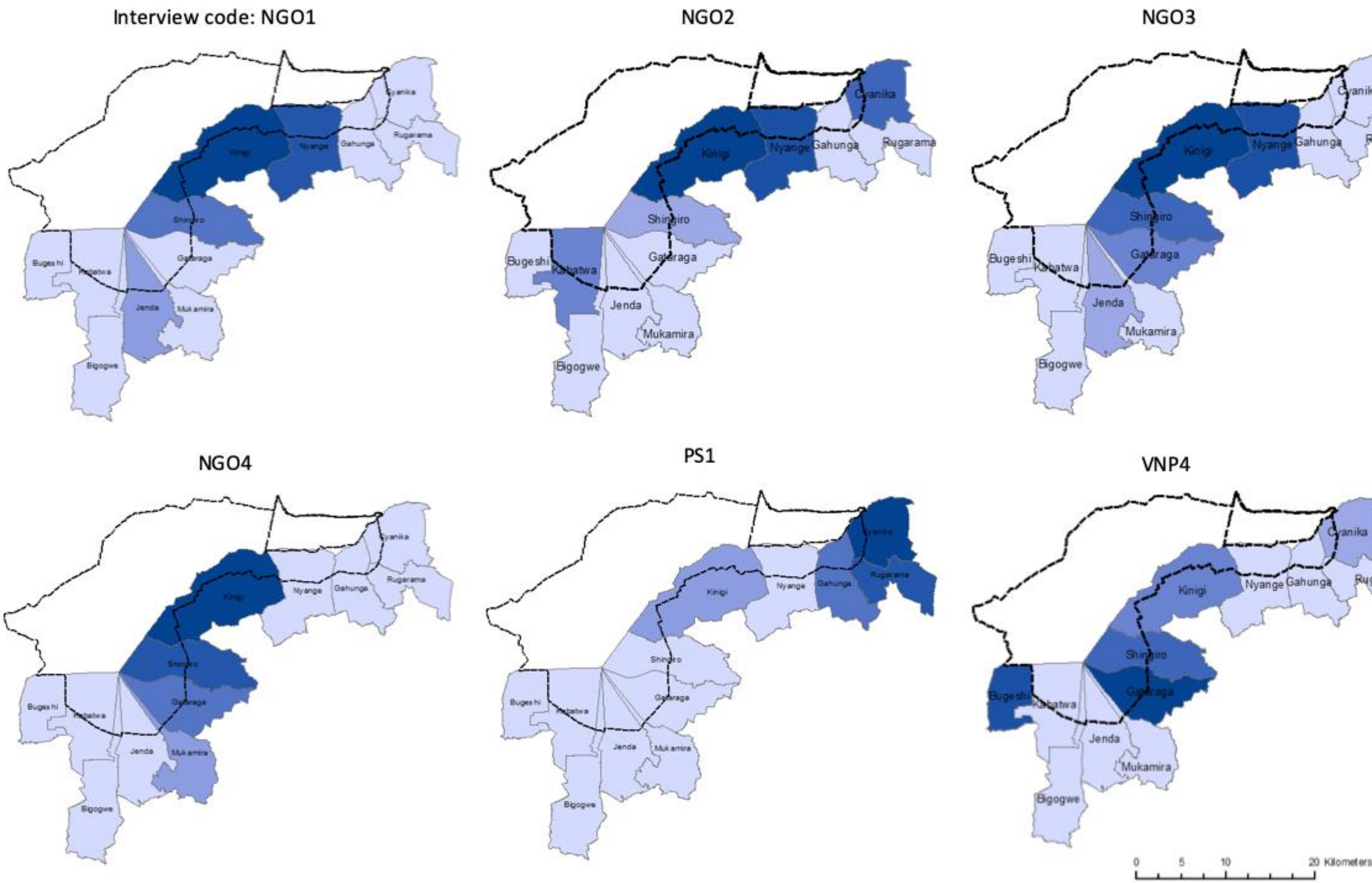
SUPPLEMENTARY TABLE 2 Models 1 and 2 present results of site-demeaned fixed effects regression excluding water projects from the tourism revenue-sharing (TRS) and NGO variables (e.g., water tanks) and incidents of water collection inside the park from the illegal activity variables. Models 3 and 4 present the results of site-demeaned fixed effects regression for only water projects and only incidents of water collection. CPUE is catch per unit effort-corrected. Fixed effect absorbing for 12 sectors. For M1 and M2, n=120; for M3 and M4 n=119. Robust standard errors clustered to sector in parentheses. *** p<0.01, **p<0.05, *p<0.1.

	1 No water *Illegal* *(uncorrected)*	*2* No water *CPUE* *(corrected)*	*3* Water only *Illegal* *(uncorrected)*	*4* Water only *CPUE* *(corrected)*
TRS	0.002862 (0.0025891)	0.0015157 (0.0014889)	-0.0118664* (0.0065911)	-0.006571 (0.0039264)
CNGO	-0.0004648* (0.003005)	-0.0002871* (0.001699)	-0.000422* (0.0002584)	-0.002294* (0.001554)
year	40.82178** (15.58602)	21.25039** (8.478902)	14.19274 (10.23828)	7.743022 (5.759288)
pop. density	1.635829* (0.7808678)	0.9086083* (0.4309772)	1.705419* (0.8016631)	0.9700451 (0.4596986)
precipitation	7.164552** (2.759468)	4.162216** (1.614687)	2.008282 (1.289092)	1.085095 (0.7191623)
R^2	0.6383	0.6201	0.5406	0.5439

SUPPLEMENTARY TABLE 3 Qualitative Data Collection Instruments.

Interviewee Code	Role	Funding focus
CNGO1	Practitioner	TRS/CNGO
CNGO2	Practitioner	TRS/CNGO
CNGO3	Practitioner	CNGO
CNGO4	Practitioner	CNGO
PSI1	CEO	PS
PSI2	Employee	PS
VNP1	Warden	TRS/CNGO/PS
VNP2	Warden	TRS/CNGO
VNP3	Warden	TRS/CNGO
VNP4	Warden	TRS
VNP5	Warden	TRS

Please directly request interview questions from authors.



SUPPLEMENTARY FIG. 7 Mapping qualitative data. Qualitative-GIS from mapping interviews, visualizing interviewee differences in sector prioritization for ICDP investment. Each map corresponds to one interviewee (see Supplementary Table 3). Interviewees were asked to rank the top five sectors for projects based on their organizational mandate/perception of "problem areas." Fig. 5a shows these values averaged, alongside the legend. Fig. 5b shows actual sectors of origin for poachers apprehended 2011-2015 for reference.