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Community-based rangeland management in Namibia improves resource governance but not environmental and economic outcomes

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Classic theories suggest that common pool resources are subject to overexploitation. Community-based resource management approaches may ameliorate tragedy of the commons effects. Here we use a randomized evaluation in Namibia's communal rangelands to study a comprehensive four-year program to support community-based rangeland and cattle management. We find that the program led to persistent and large improvements for eight of thirteen indices of social and behavioral outcomes. Effects on rangeland health, cattle productivity and household economics, however, were either negative or nil. Positive impacts on community resource management may have been offset by communities' inability to control grazing by non-participating herds and inhibited by an unresponsive rangeland sub-system. This juxtaposition, in which measurable improvements in community resource management did not translate into better outcomes for households or rangeland health, demonstrates the fragility of the causal pathway from program implementation to intended socioeconomic and environmental outcomes. It also points to challenges for improving climate change–adaptation strategies.

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In his seminal 1968 essay, "The Tragedy of the Commons," Garrett Hardin argued that poorly managed common resources are subject to overexploitation[1]. Hardin explained the tragedy of the commons using the metaphor of "a pasture open to all" in which each herd owner receives individual benefits from accumulating livestock while sharing the cost of overgrazing with other community members. This "natural" promotion of self-interest harms the common resource and ultimately brings ruin to all herders. Today, rangeland degradation is not only a textbook metaphor for the tragedy of the commons theory, but highly relevant globally: Drylands occupy 41% of the Earth's land area, support two billion people, and are experiencing rapid environmental degradation exacerbated by climate change, and in many cases attributable to overuse from livestock and crop agriculture[2]. Strategies for coping with impending climate change are critical for local and global policy.

Hardin concluded that the tragedy of the commons can be prevented only by coercive government regulation or resource privatization. However, Elinor Ostrom and other critics of Hardin's thesis have documented numerous communities that successfully developed local management systems to avoid overexploitation of commonly held resources, including rangelands[3–11]. These findings have generated considerable enthusiasm for programs undertaken by governmental and non-governmental organizations that provide external support for holistic, community-based management of natural resources[2,12,13].

But observing that some communities have developed successful systems of collective management does not mean that collective management instigated by outside organizations will succeed, and assessing the efficacy of such external interventions poses classic evaluation challenges. It is difficult to identify the impact of interventions because of external factors such as weather and macroeconomic conditions, and because of unobserved community or individual traits that drive both program participation and successful community management. Measurement is difficult because impacts are expected across many domains of a social-ecological system and at different points in time[14]. Related evidence from recent randomized evaluations suggests that community-driven programs can successfully deliver infrastructure and economic returns, but have less success sustainably affecting community governance and the creation of social capital[15].

We evaluated an integrated program in Namibia's Northern Communal Areas (NCAs) that promoted improved rangeland and livestock management among cattle-owning households. Namibia's NCAs have a population of about 1.2 million people, predominantly pastoralists and agro-pastoralists, who herd cattle and small ruminants using traditional methods and grow crops (i.e., millet, maize) under non-irrigated conditions[16] Rangeland vegetation and soils have been degraded by pressure from growing populations and reduced herd mobility (see Supplementary Note 1 for details). Low-input management results in uncoordinated livestock grazing and overuse of local resources. Resource management in the NCAs is further complicated by climate change[17]. For example, climate change may increase the prevalence of drought and bush encroachment, which are already destabilizing rangeland ecosystems in the NCAs[2,18].

The economic and ecological challenges facing the NCAs are partially traceable to three features of colonial-era land administration. First, in 1897 German colonial authorities established a veterinary cordon fence (VCF) separating the NCAs from southern Namibia to prevent the spread of livestock disease. Restrictions on movement and sale of livestock from northern to southern Namibia remain in place today, severely limiting the development of the formal livestock sector in the NCAs. Second, between 1897 and 1962, German and South African colonial authorities expropriated land from hundreds of thousands of black Namibians and relocated them to marginal communal lands known as "native reserves" on both sides of the VCF[19,20]. The native reserve policy restricted private land and capital accumulation by black Namibians and eroded customary land governance institutions in communal areas[19,21]. Finally, in 1962 the South African government, which took over the administration of Namibia from Germany following World War I, funded widespread borehole development in the NCAs to address growing political unrest. This dramatic expansion of water infrastructure, which was carried out with minimal concern for ecological consequences or investment in local resource governance, severed the link between grazing movements and the availability of natural water sources and catalyzed the growth of human and livestock populations, laying the groundwork for many of the ecological challenges that northern Namibia faces today[16,22].

The Community Based Rangeland and Livestock Management program (CBRLM) was part of a four-year partnership between the Millennium Challenge Account-Namibia and the Government of Namibia to reduce rangeland degradation and promote economic development. From 2010 to 2014 the implementing partner, Gesellschaft für Organization, Planung und Ausbildung (GOPA), worked with communities to jointly develop locally tailored rangeland grazing management, livestock management, and livestock marketing plans. GOPA then offered multi-faceted support to communities that established committees to coordinate and monitor these resource management plans. GOPA's support included water-infrastructure development, trainings on animal husbandry, livestock marketing, and rangeland management, livestock loans, matching grants, and technical assistance from trained field facilitators.

The rangeland management approach underlying CBRLM centered on combined herding and planned grazing. The program encouraged participating community members to combine household cattle herds into larger herds and rotate them among pre-planned sites within the grazing area. Planned rotation allows for vegetation rest and recovery and the establishment of dry-season fodder reserves, while combined herding improves grazing coordination and reduces the costs of herding. CBRLM field facilitators also encouraged enhanced livestock sales and flexible stocking rates to optimize grazing pressure. According to CBRLM's theory of change, improved management practices and enhanced cattle sales would improve communities' economic well-being while reducing the risk of rangeland degradation (see "Methods").

To overcome attribution and measurement challenges, we conducted a large-scale, randomized evaluation and included multi-disciplinary measurement of behavioral, economic, livestock, and rangeland outcomes up to seven years after the program was initiated. The main questions posed were: (1) Can external support cause improvements in community resource management that persist two years after the support ends? (2) What is the effect of external support for community resource management on rangeland health, cattle productivity, and household well-being?

We find that program generated substantial and persistent improvements in rangeland grazing management, community governance, and collective action. Effects on rangeland health, cattle productivity and household economics, however, were either negative or nil. Positive impacts on community resource management may have been offset by communities' inability to control grazing by non-participating herds and inhibited by an unresponsive rangeland sub-system. This juxtaposition, in which measurable improvements in community resource management did not translate into better outcomes for households or rangeland

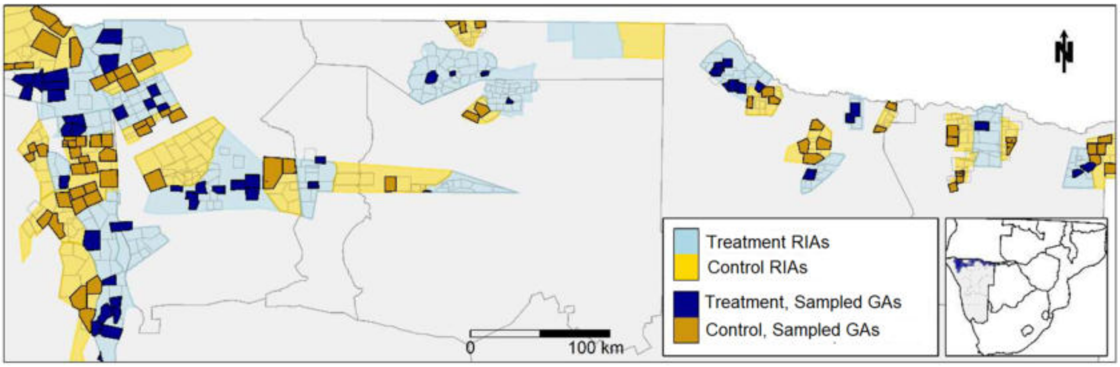

Fig. 1 Distribution of rangeland intervention areas (RIAs) and grazing areas (GAs) for CBRLM in northern Namibia. Blue and yellow colors identify treatment and control RIAs, respectively. Darker shading identifies the GAs that were sampled for measurement.

health, demonstrates the fragility of the causal pathway from program implementation to intended socioeconomic and environmental outcomes.

Results

Study design. In order to select study areas, GOPA mapped 38 Rangeland Intervention Areas (RIAs), intervention zones with locally recognized boundaries and sufficiently low density of people, livestock, and bush cover to enable the implementation of new group-grazing plans. Each RIA comprised 5–15 Grazing Areas (GAs), communal rangeland parcels shared by 5–35 households. We randomly assigned 19 RIAs to treatment and 19 RIAs to control, and measured program outcomes in 123 selected GAs (52 treatment and 71 control, see "Methods"). Fig 1 displays the GAs in treatment and control RIAs; darker shades identify the GAs sampled for measurement. Inference was computed using clustered standard errors and randomization inference, due to the 38-unit clustered design.

To measure resource management behaviors, we conducted 1241 and 1348 surveys of cattle herd managers at program end and two years later, respectively. We confirmed key practices with direct observation audits conducted after each survey. To assess impacts on rangeland condition two years after program end, we collected vegetation and soil data via randomly-sampled 1-ha sites during the wet (Apr-May) and dry (Sep-Oct) seasons. To assess impacts on cattle health and productivity two years after program end, we weighed, aged, and assessed body condition scores of 20,000 cattle in 730 herds during the dry season. Finally, to assess impacts on household economic outcomes three years after program end, we conducted 1345 household surveys. We used ordinary least squares regression with standard errors clustered at the RIA level to estimate treatment effects.

Treatment effects on social and behavioral outcomes. Fig 2 illustrates impacts of CBRLM on standardized indices of social and behavioral outcomes (see "Methods" for details of the composition and construction of indices). At program end, we find large, statistically significant effects on eight of thirteen social indices: grazing planning (+1.31 sd, $p < 0.001$), grazing-plan adherence (+0.35 sd, $p < 0.001$), herding practices (+0.37 sd, $p = 0.003$), herder management (+0.15 sd, $p = 0.07$), cattle husbandry (+0.36 sd, $p = 0.002$), community governance (+0.75 sd, $p < 0.001$), collective action (+1.53 sd, $p < 0.001$), and expertize (+0.30 sd, $p = 0.005$). We do not observe statistically significant improvements in herd restructuring (+0.00 sd, $p = 0.95$), cattle marketing (−0.06 sd, $p = 0.37$), community disputes (+0.07 sd, $p = 0.34$), trust (−0.02 sd, $p = 0.73$), or perceptions of self and community efficacy (+0.04 sd, $p = 0.67$) (also see Tables 1, 2, and 3).

To illustrate program influences on collective action we highlight two key outcomes: At program end, planned grazing with peers increased by 28 percentage points (control mean = 22%, $p < 0.001$) while combining cattle with those of peers increased by 34 percentage points (control mean = 38%, $p < 0.001$) (Table 3). Patterns were validated via direct observation audits (Supplementary Table 8).

Two years after program end, improvements in all four indices of rangeland grazing management persisted: grazing planning (1.02 sd, $p < 0.001$), grazing-plan adherence (0.32 sd, $p < 0.001$), herding practices (0.30 sd, $p = 0.001$), and herder management (0.43 sd, $p = 0.004$), as did positive effects on community governance (0.55 sd, $p < 0.001$), collective action (0.89 sd, $p < 0.001$), and expertize (0.35 sd, $p < 0.001$). Improvements in cattle husbandry were smaller and no longer statistically significant (0.13 sd, $p = 0.19$). Community disputes increased due to disagreements both within and between grazing communities over access to program-generated resources such as water developments and forage reserves (−0.29 sd, $p = 0.002$) (Tables 1 and 3).

Treatment effects on rangeland health, cattle productivity, and household economics. Fig 3 illustrates results concerning our second research question, namely whether changes in resource management translated to improved rangeland health, cattle productivity, and household economics. No statistically significant effects were observed for herd productivity two years after program end or for household outcomes three years after program end. Of 10 rangeland outcomes measured two years after program end, four showed statistically significant but negative effects (Tables 4, 5, and 6). We observed these adverse effects on key rangeland outcomes during the wet season, including 4 percentage points lower protected soil surface (control mean = 81% protected, $p = 0.05$), 3 percentage points lower plant litter cover (control mean = 55%, $p = 0.04$), 8 percentage points lower herbaceous canopy cover (control mean = 45%, $p = 0.07$), and a 121 kg/ha decrease in fresh plant biomass (control mean = 459 kg/ha, $p = 0.10$). These are indicators of declining ecosystem health. We also observed a 5 percentage-point reduction in herbaceous canopy cover (control mean = 22%, $p = 0.002$) and a 6 kg/ha reduction in fresh plant biomass during the dry season (control mean = 233 kg/ha $p = 0.004$), illustrating that the CBRLM failed to enhance fodder reserves for risk management purposes (see Table 6).

Discussion

We find that an external intervention to support community-based resource management generated substantial and persistent

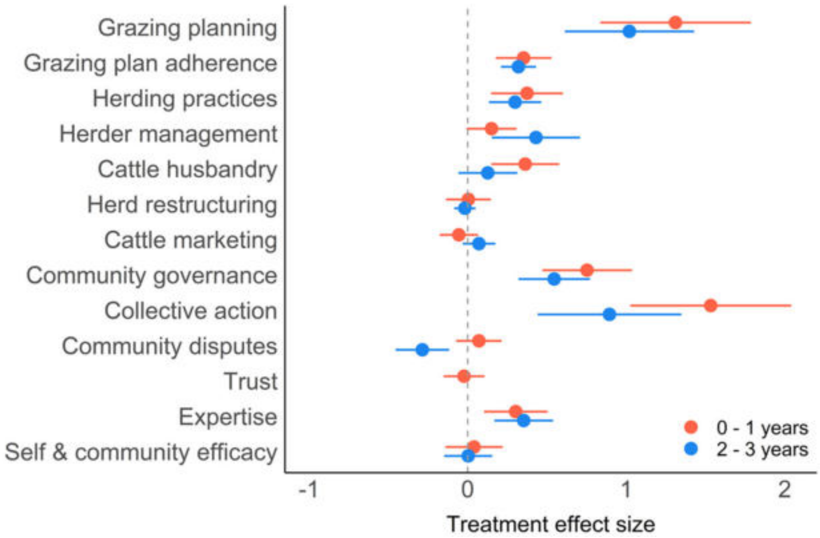

Fig. 2 Effect of community-based rangeland management (CBRLM) on 13 indices of social and behavioral outcomes. Orange markers denote results 0–1 years after program end (2014) and blue markers denote results 2–3 years after program end (2016). For each index the mid-point is the standardized treatment effect size, with a corresponding 95% confidence interval. Supporting statistical results are shown in Table 1.

improvements in rangeland grazing management, community governance, and collective action. However, effects on rangeland, livestock, and household attributes were mostly nil, and in some cases negative.

The null to negative effects on rangeland condition are most likely the result of CBRLM increasing, rather than reducing, grazing intensity. For example, relative to control sites, sites in treatment areas were 12 percentage points more likely to be heavily grazed in the wet season (control mean = 13%, $p = 0.003$) and 10 percentage points more likely to be heavily grazed in the dry season (control mean = 46%, $p = 0.02$) of 2016 (see Table 7). While we find no evidence that CBRLM increased the number of cattle herds or the number of cattle per herd in treatment areas, we did observe that non-CBRLM-participating herd owners from inside and outside treated areas exploited the treated GAs. Relative to herd owners in control areas, herd owners in treatment GAs were seven percentage points more likely to report observing "uninvited herds" in their GA in the previous year (control mean = 16%, $p = 0.005$). We speculate that the incentives for outsiders to "poach" forage in treated areas were strong in the dry season because of CBRLM investments in water infrastructure and encouragement of CBRLM herd owners to set aside un-grazed forage reserves. Thus, one consideration for future implementation and research is completeness of coverage: had implementation been able to cover all areas, then this would have reduced the risk of such incursions. These effects were compounded by the program's failure to stimulate opportunistic livestock off-take through livestock marketing.

Null effects on rangeland outcomes may also have resulted from an unresponsive rangeland sub-system. In this sense, our findings mirror the outcomes from other integrated, grazing management programs for commercial ranching in developed nations. Namely, ecologically based processes exhibit sizable temporal inertia relative to management and social outcomes[23,24]. Temporal lags between primary and secondary productivity can be exacerbated by the precipitation variability that characterizes northern Namibia[25]. Even if the CBRLM grazing management schemes had been perfectly implemented with reduced stocking rates, adequate protection from grass poachers and favorable rainfall regimes, rangeland responsiveness to the treatment may have been limited by the nonequilibrium characteristics of forage—dominated by annual grasses—and pervasive soil degradation (see "Methods").

Nonetheless, further tracking of outcomes may be fruitful, and it is possible that positive economic or ecological outcomes will manifest over longer periods of time. While we do not observe early indicators of positive ecological or economic change, we also do not have a strong prediction based on outside literature as to whether impacts will improve, worsen or remain the same. We also recognize that improvements in social outcomes such as governance or collective action may offer intrinsic benefits to communities.

Hardin proposed that effective management of the commons under population pressure requires either coercive regulation or resource privatization[1] (neither of which is politically realistic in many contexts in low-income countries). Inspired by Ostrom's theories of community resource management, CBRLM took a third path by investing in local institutions to arrest environmental degradation.

Our findings should temper overly optimistic views of what external interventions to promote community-based resource management can achieve in dryland situations to cope with climate change. Although it is important to note, as with any evaluation, our findings are particular to the specific program studied. Should our results temper enthusiasm for the theory of change, or are the results that did not match the aspirations more a consequence of specific programmatic decisions or imperfect implementation? The program studied took a holistic approach to CBRLM, whereas the broad concept of community-based resource management clearly could encompass a different set of components. For instance, water infrastructure development as implemented may have increased participation rates and provided direct benefits to the communities but at the cost of increased incursions by outside herds. On implementation, the process data do reveal high levels of participation and strong, positive feedback indicators, suggesting strong implementation fidelity (although a question remains whether the theory of change requires an even higher participation rate than achieved).

When designing future programs to support improved community-based responses to climate change and ecological degradation, policymakers should integrate complementary strengths, resources, and wisdom from local (e.g., traditional), regional and national authorities to address commons management challenges[26,27]. One focal area should be how to better design and enforce property rights for land, water, and grazing

Table 1 Treatment effect on social indices.

Dependent variable	0–1 years after program end						2–3 years after program end					
	coef.	SE	*p* val.	RI *p* val.	*q* val.	*N*	coef.	SE	*p* val.	RI *p* val.	*q* val.	*N*
Panel A: Behaviors												
Grazing planning	1.31	0.24	<0.001	0.002	0.001	1199	1.02	0.21	<0.001	0.002	0.001	1218
Grazing plan adherence	0.35	0.09	<0.001	0.034	0.001	1199	0.32	0.06	<0.001	0.002	0.001	1240
Herding practices	0.37	0.12	0.003	0.013	0.001	1199	0.30	0.08	0.001	0.023	0.002	1243
Herder management	0.15	0.08	0.069	0.133	0.072	1199	0.43	0.14	0.004	0.058	0.005	1243
Cattle husbandry*	0.36	0.11	0.002	0.029	.	1199	0.13	0.09	0.190	0.354	.	1249
Herd restructuring*	0.00	0.07	0.952	0.977	.	1199	−0.02	0.03	0.604	0.777	.	1243
Cattle marketing*	−0.06	0.06	0.374	0.655	.	1199	0.07	0.05	0.184	0.474	.	1245
Panel B: Community dynamics, knowledge, and attitudes												
Community governance	0.75	0.14	<0.001	0.007	0.001	1199	0.55	0.12	<0.001	0.004	0.001	1245
Collective action	1.53	0.26	<0.001	0.002	0.001	1199	0.89	0.23	<0.001	0.002	0.002	1245
Community disputes	0.07	0.07	0.339	0.458	0.466	1140	−0.29	0.09	0.002	0.108	0.004	1243
Trust	−0.02	0.07	0.729	0.786	0.803	1198	.	.	.	.	.	.
Expertize	0.30	0.10	0.005	0.044	0.009	1199	0.35	0.09	<0.001	0.011	0.002	1248
Self & community efficacy	0.04	0.09	0.668	0.754	0.803	1196	0.00	0.08	0.970	0.980	0.971	1009

Notes: Each coef. is the coefficient on the treatment variable in an OLS regression of an index of social or behavioral outcomes on treatment status. It is an intent-to-treat (ITT) estimate relative to the control group. Standard errors are clustered at the RIA level, i.e., the unit of randomization. RI *p* values are calculated using randomization inference. Each regression includes as controls a categorical variable for traditional authority (an administrative unit) that was used for block stratification and the RIA-level variables used in re-randomization to ensure balance, which are: vegetation type, number of livestock, livestock density, the log of the number of CBRLM-eligible households, and binary indicators for whether the RIA overlaps with prior intervention areas, has a quality water source, and has a community based organization. Indices are the standardized (mean = 0 and sd = 1), unweighted average of standardized components. See "Materials and Methods" for details of index construction. Variables for the "trust" index were not collected in the survey 2–3 years after program end. All *p* values are two-tailed.

*Indicates variables for which multiple hypothesis correction was not specified in the pre-analysis plan.

resources. The design of these rights should reflect the varied levels (e.g., household vs. community) at which different resources are managed and utilized and incorporate historical perspectives about how social, economic, and ecological sub-systems have evolved and interacted over time[10,11,16,28–30]. Innovative livestock marketing programs could be considered to better address structural constraints and incorporate cultural perspectives of producers. Finally, policymakers could explore well-tested alternative livelihood programs to achieve development goals in light of the long-time horizon and uncertain effects of programs to support new community-management systems[31–33].

In addition to its theoretical and practical implications, this research demonstrates the value of providing experimental evidence on impacts of community-based development programs in a policy-relevant setting. Many experimental studies of resource management are conducted using tightly managed plots under direct researcher control, limiting their relevance for answering real-world policy questions[24]. On the other hand, field studies of community-based resource management programs typically rely on non-experimental evidence that may be biased due to self-selected participation or unobserved social, ecological, or economic factors. Given the importance of resource management, particularly with increasing issues from climate change, further research is needed to identify the contexts, approaches, and program components that yield strong and inclusive impacts[12].

Methods

Theory of change. At the heart of the of CBRLM's theory of change is the assumption that improvements in the ecological sub-system provide a sustainable resource base for increased livestock production and marketing[34]. The ecological sub-system, however, depends on a functioning economic sub-system because herd owners must be able to destock quickly in response to adverse ecological circumstances. The theory holds that the most important constraint on the economic sub-system is unproductive herds and low-quality cattle because farmers are unwilling to sell their cattle when they command low market prices. Therefore, improvements in rangeland grazing management need to be complemented by improvements in information and access to livestock markets, herd structures, and animal husbandry practices.

Crucially, changes to the ecological, economic, and livestock sub-systems rely on effective community governance and collective-action capacity in CBRLM communities. This is because rangeland grazing management practices can be easily undermined by non-participating herd owners inside or outside the GA. The theory therefore calls for investments at multiple levels of the social-ecological system to ensure that improvements in certain program areas are not undermined by failures in others[34]. The CBRLM implementers believed that previous rangeland development programs were undermined by a failure to account for the linkages among sub-systems, which motivated them to design a more holistic intervention[34].

Intervention components. CBRLM was a multi-faceted package of administrative, educational, financial, and technical support. Implementation of the package was designed as an experimental treatment to assist in project assessment. To select study areas for evaluation, GOPA identified 38 RIAs with sufficiently low density of people, livestock, and bush cover to enable the implementation of new group-grazing plans, one of the core treatment components. The evaluation team randomly assigned 19 RIAs to treatment and 19 RIAs to control (see Randomization for details). GOPA implemented CBRLM in up to seven GAs within each treatment RIA.

Mobilization. GOPA conducted pre-mobilization meetings with TAs and other stakeholders in the second half of 2010 to identify GA communities most likely to participate in CBRLM[34]. Early mobilization efforts focused on soliciting community buy-in for the cornerstone principles of CBRLM, including community-planned grazing, combined herding of cattle, and efficient livestock management. There is also substantial evidence from qualitative surveys that some community members were motivated to participate in the CBRLM by prospects for water infrastructure development by GOPA[34].

While almost 100 GAs were initially mobilized for the project, by 2014 GOPA was targeting resources and support towards 58 GAs based on community receptivity and the discretion of CBRLM management. In each GA, GOPA worked principally with households owning 10 or more cattle, although other community

Table 2 Treatment effect on social indices and their components (Panel A).

Panel A: Behavioral outcomes	0–1 years after program end						2–3 years after program end					
Dependent variable	coef.	SE	*p* val.	RI *p* val.	Ctrl mean	*N*	coef.	SE	*p* val.	RI *p* val.	Ctrl mean	*N*
Index: Grazing planning	1.31	0.24	<0.001	0.002	0.00	1199	1.02	0.21	<0.001	0.002	0.00	1218
Manager has grazing plan	0.08	0.04	0.032	0.215	0.67	1199	0.13	0.03	<0.001	0.002	0.62	1217
Manager can show written grazing plan	0.27	0.05	<0.001	0.001	0.01	1182	0.20	0.05	<0.001	0.002	0.03	1218
Manager has grazing plan for next season	0.18	0.03	<0.001	0.006	0.45	1199	.	.	.	.	.	.
Index: Grazing plan adherence	0.35	0.09	<0.001	0.034	0.00	1199	0.32	0.06	<0.001	0.002	0.00	1240
Manager followed grazing plan*	0.17	0.03	<0.001	0.017	0.40	1199	0.09	0.03	0.002	0.024	0.25	1218
Number of months followed plan (past year)	0.88	0.39	0.030	0.178	5.00	1186	1.63	0.32	<0.001	0.005	4.03	1181
Index: Herding practices	0.37	0.12	0.003	0.013	0.00	1199	0.30	0.08	0.001	0.023	0.00	1243
Someone herds manager's cattle	0.06	0.04	0.113	0.192	0.78	1199	0.02	0.03	0.455	0.780	0.82	1225
Herder stays with cattle throughout day*	0.11	0.03	<0.001	0.020	0.40	1199	0.09	0.03	0.002	0.024	0.25	1218
Cattle herded from water point in bunch	0.16	0.06	0.007	0.041	0.21	1199	.	.	.	.	.	.
Cattle herded in bunch when grazing	0.13	0.04	0.004	0.023	0.14	1199	0.11	0.04	0.019	0.045	0.16	1243
No cattle missing from manager's herd	0.00	0.03	0.916	0.960	0.56	1199	.	.	.	.	.	.
(−1)*Ratio of cattle lost/stolen to cattle owned	−0.01	0.03	0.848	0.877	−0.14	1187	−0.01	0.01	0.373	0.538	−0.06	1234
Grazing plan intended to protect grass	.	.	.	.	.	.	0.13	0.05	0.010	0.045	0.19	819
Index: Herder management	0.15	0.08	0.069	0.133	0.00	1199	0.43	0.14	0.004	0.058	0.00	1243
Manager communicates weekly with herders	0.05	0.04	0.203	0.442	0.67	1198	.	.	.	.	.	.
Manager pays herders in cash	0.09	0.04	0.019	0.106	0.28	1198	0.04	0.05	0.405	0.725	0.55	1243
Total cash & in-kind payment to herders (NAD)	64.97	35.64	0.076	0.132	252.95	1196	60.45	69.11	0.387	0.585	463.78	1204
Total spent on gear provided to herders (NAD)	.	.	.	.	.	.	−4.93	102.86	0.962	0.975	462.14	994
Total gear provided to herders (# of items)	−0.04	0.09	0.651	0.781	1.00	1195	.	.	.	.	.	.
Index: Cattle husbandry	0.36	0.11	0.002	0.029	0.00	1199	0.13	0.09	0.190	0.354	0.00	1249
Cattle visit water point at least once per day	0.17	0.05	<0.001	0.020	0.18	1199	.	.	.	.	.	.
Any non-mandatory cattle vaccination	0.07	0.05	0.158	0.366	0.54	1199	0.04	0.05	0.416	0.603	0.59	1242

Table 2 (continued)

Panel A: Behavioral outcomes	0–1 years after program end						2–3 years after program end					
Dependent variable	**coef.**	**SE**	***p* val.**	**RI *p* val.**	**Ctrl mean**	***N***	**coef.**	**SE**	***p* val.**	**RI *p* val.**	**Ctrl mean**	***N***
Cumulative number of cattle vaccinations	0.17	0.09	0.071	0.257	0.83	1199	.	.	.	.	.	.
Total spent on cattle vaccines (NAD)	.	.	.	.	.	.	163.86	71.88	0.028	0.146	603.19	1220
Cattle have been dewormed	0.08	0.04	0.032	0.124	0.17	1199	0.02	0.04	0.608	0.652	0.30	1243
Number of cattle dietary supplements provided	0.11	0.09	0.236	0.464	0.93	1199	0.18	0.12	0.165	0.345	1.39	1242
Cattle checked for ticks at least monthly	0.04	0.03	0.172	0.512	0.35	1199	−0.02	0.04	0.636	0.770	0.38	1243
Total investment in animal treatment (NAD)	.	.	.	.	.	.	−50.68	95.97	0.601	0.809	462.07	1222
Fraction of cattle eartagged	.	.	.	.	.	.	0.04	0.03	0.172	0.276	0.84	653
Index: Herd restructuring	0.00	0.07	0.952	0.977	0.00	1199	−0.02	0.03	0.604	0.777	0.00	1243
Sold cattle to improve herd structure	0.00	0.03	0.952	0.977	0.30	1199	0.00	0.01	0.604	0.777	0.05	1243
Index: Cattle marketing	−0.06	0.06	0.374	0.655	0.00	1199	0.07	0.05	0.184	0.474	0.00	1245
Any live cattle sold (past year)	0.00	0.03	0.978	0.990	0.58	1199	0.04	0.02	0.067	0.226	0.36	1243
Total number of live cattle sold (past year)	−0.47	0.41	0.263	0.614	3.66	1190	0.18	0.26	0.506	0.698	1.67	1245
Total value of live cattle sold (NAD, past year)	−2321	1809	0.208	0.567	11,471	1157	1246	1055	0.245	0.561	7108	1226

Notes: See Table 1 notes for details on regression specification. Each index is the standardized (mean = 0 and sd = 1), unweighted average of the standardized components listed below it; see "Materials and Methods" for a complete description of index creation. Empty cells indicate that a variable was not collected in that survey round. Monetary variables are in Namibian dollar (NAD) amounts. 0–1 years after program end (2014), the exchange rate was 10.8 NAD to 1 USD, and 2–3 years after program end was 14.7 NAD to 1 USD. Component variables without description of units are binary, with positive responses coded as 1. All *p* values are two-tailed.

*Indicates that the survey question used to construct the variable asked about behaviors during the past rainy season in the survey conducted 0–1 years after program end, and behaviors during the past year in the survey conducted 2–3 years after program end.

Table 3 Treatment effect on social indices and their components (Panel B).

Panel B: Community dynamics, knowledge, and attitudes	0–1 years after program end						2–3 years after program end					
Dependent variable	**coef.**	**SE**	***p* val.**	**RI *p* val.**	**Ctrl mean**	***N***	**coef.**	**SE**	***p* val.**	**RI *p* val.**	**Ctrl mean**	***N***
Index: Community governance	0.75	0.14	<0.001	0.007	0.00	1199	0.55	0.12	<0.001	0.004	0.00	1245
GA community groups, past 5 yrs (# of groups)	.	.	.	.	.	.	0.36	0.06	<0.001	0.010	1.54	1243
GA community groups currently (# of groups)	.	.	.	.	.	.	0.32	0.08	<0.001	0.049	1.47	1243
Manager's cumulative membership (# of groups)	0.46	0.09	<0.001	0.026	0.70	1199	0.30	0.08	<0.001	0.060	0.78	1244
Group performance (# of satisfying groups)	.	.	.	.	.	.	0.86	0.21	<0.001	0.041	3.69	1243
Farmers enforce water point payments	.	.	.	.	.	.	0.03	0.05	0.578	0.742	0.65	1243
Farmers pay for water according to usage	.	.	.	.	.	.	0.02	0.06	0.759	0.821	0.19	1239
Grazing plan formally enforced	.	.	.	.	.	.	0.05	0.02	0.010	0.083	0.04	1243
Someone personally enforces grazing plan*	0.30	0.05	<0.001	0.004	0.13	1198	0.26	0.05	<0.001	0.003	0.13	1217
Non-community grazing not allowed	.	.	.	.	.	.	0.07	0.02	0.005	0.070	0.16	1230
Conflict resolution is group-based	.	.	.	.	.	.	0.09	0.02	<0.001	0.041	0.60	1243
Satisfied with group conflict resolution (1–3 scale)	.	.	.	.	.	.	−0.07	0.04	0.147	0.235	2.67	1225
Approves of traditional authority	−0.01	0.03	0.681	0.845	0.25	1175	.	.	.	.	.	.
Index: Collective action	1.53	0.26	<0.001	0.002	0.00	1199	0.89	0.23	<0.001	0.002	0.00	1245
Manager pays herders communally	0.08	0.01	<0.001	0.023	0.02	1199	0.11	0.03	<0.001	0.036	0.28	1240
Pays for vaccines communally	0.15	0.04	<0.001	0.013	0.03	1199	.	.	.	.	.	.
Pays for cattle care communally	.	.	.	.	.	.	0.05	0.07	0.457	0.646	0.32	1243
Attended water committee >4x yearly*	0.05	0.03	0.098	0.162	0.11	1199	0.04	0.02	0.094	0.156	0.12	1239
Contributed money to water committee	0.11	0.03	<0.001	0.025	0.19	1199	0.04	0.04	0.320	0.503	0.25	1243
Water committee contribution amt (NAD)	.	.	.	.	.	.	43.72	67.97	0.524	0.609	138.89	1230
Attended development committee >4x yearly	0.01	0.01	0.343	0.609	0.06	1199	0.02	0.01	0.185	0.498	0.05	1238
Contributed money to development committee	0.04	0.01	<0.001	0.070	0.05	1196	.	.	.	.	.	.
Development committee contribution amt (NAD)	.	.	.	.	.	.	−0.14	1.57	0.930	0.967	5.25	1233
Practiced rainy season combined herding*	0.34	0.04	<0.001	0.004	0.38	1188	0.19	0.07	0.008	0.033	0.36	1217
Intentionally combined cattle with specific herd*	0.34	0.06	<0.001	0.004	0.20	1199	.	.	.	.	.	.
Ratio of GA herds to herds in combined herd*	0.23	0.05	<0.001	0.003	0.05	1089	0.12	0.04	0.001	0.011	0.04	1216
Ratio of manager cattle to combined herd cattle*	0.21	0.06	<0.001	0.007	0.03	1039	0.12	0.03	<0.001	0.009	0.03	1186
Grazing plan is decided on by group*	0.28	0.05	<0.001	0.004	0.22	1189	0.24	0.05	<0.001	0.006	0.26	1218
Shared grazing plan exists for rainy season*	0.19	0.04	<0.001	0.012	0.32	1199	.	.	.	.	.	.
Ratio of farmers in group grazing plan to GA herd*	0.18	0.04	<0.001	0.020	0.13	1171	0.16	0.05	0.002	0.018	0.15	1218
Attended grazing committee >4x yearly	0.16	0.03	<0.001	0.009	0.03	1199	0.10	0.02	<0.001	0.002	0.02	1243

Table 3 (continued)

Panel B: Community dynamics, knowledge, and attitudes	0–1 years after program end						2–3 years after program end					
Dependent variable	coef.	SE	*p* val.	RI *p* val.	Ctrl mean	*N*	coef.	SE	*p* val.	RI *p* val.	Ctrl mean	*N*
Contributed money to grazing committee	0.16	0.04	<0.001	0.007	0.02	1197	0.05	0.01	<0.001	0.013	0.02	1243
Grazing committee contribution amt (NAD)	.	.	.	.	.	.	11.12	4.85	0.028	0.157	4.90	1239
Index: Community disputes	0.07	0.07	0.339	0.458	0.00	1140	−0.29	0.09	0.002	0.108	0.00	1243
Community conflicts decreased (past 3 yrs)*	0.03	0.03	0.339	0.458	0.30	1140	.	.	.	.	.	.
Conflicts w/ farmers inside GA (−1*[# conflicts])	.	.	.	.	.	.	−0.12	0.03	<0.001	0.082	−1.15	1243
Conflicts w/ farmers outside GA (−1*[# conflicts])	.	.	.	.	.	.	−0.08	0.03	0.012	0.182	−1.08	1243
Index: Trust	−0.02	0.07	0.729	0.786	0.00	1198	.	.	.	.	.	.
Manager believes people can be trusted	−0.05	0.04	0.249	0.414	0.49	1188	.	.	.	.	.	.
No decrease in # of people manager trusts	0.03	0.03	0.351	0.603	0.64	1177	.	.	.	.	.	.
Index: Expertize	0.30	0.10	0.005	0.044	0.00	1199	0.35	0.09	<0.001	0.011	0.00	1248
Cattle expert available for disease questions	0.18	0.05	<0.001	0.025	0.43	1199	0.17	0.06	0.003	0.020	0.31	1234
Cattle expert available for general questions	0.14	0.06	0.017	0.034	0.19	1199	.	.	.	.	.	.
Correctly ages cow based on dental condition	.	.	.	.	.	.	0.08	0.02	<0.001	0.036	0.13	1243
Manager identifies ideal bull to cow ratio	−0.03	0.03	0.331	0.405	0.20	1198	0.02	0.02	0.386	0.596	0.85	1243
Cattle weight guess (−1*[% error])	.	.	.	.	.	.	0.27	0.10	0.010	0.142	−0.54	416
Cattle market price guess (−1*[% error])	.	.	.	.	.	.	−0.02	0.02	0.418	0.587	−0.33	409
Index: Self & community efficacy	0.04	0.09	0.668	0.754	0.00	1196	0.00	0.08	0.970	0.980	0.00	1009
Own actions affect cattle health & value	0.00	0.03	0.903	0.928	0.78	1196	0.01	0.03	0.776	0.863	0.58	1009
Own actions affect rangeland quality	0.03	0.05	0.471	0.642	0.61	1195	−0.02	0.03	0.576	0.637	0.49	1009
Community engagement affects cattle health	.	.	.	.	.	.	−0.02	0.04	0.683	0.820	0.64	1009
Community actions affect rangeland	.	.	.	.	.	.	0.03	0.04	0.455	0.682	0.64	1009

Notes: See Table 1 notes for details on regression specification. Each index is the standardized (mean = 0 and sd = 1), unweighted average of the standardized components listed below it; see "Materials and Methods" for a complete description of index creation. Empty cells indicate that a variable or index was not collected in that survey round. Monetary variables are in Namibian dollar (NAD) amounts. 0–1 years after program end (2014), the exchange rate was 10.8 NAD to 1 USD, and 2–3 years after program endwas 14.7 NAD to 1 USD. Component variables without description of units are binary, with positive responses coded as 1. All *p* values are two-tailed.
*Indicates that the survey question used to construct the variable asked about behaviors during the past rainy season in the survey conducted 0–1 years after program end, and behaviors duringthe past year in the survey conducted 2–3 years after program end.

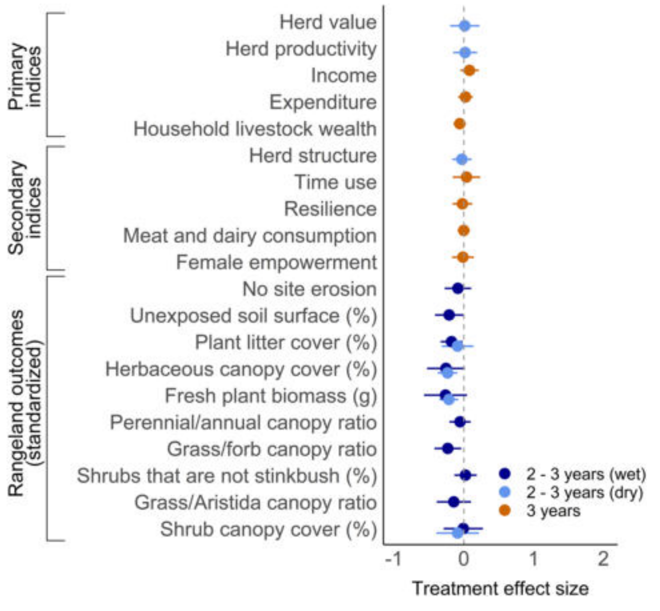

Fig. 3 Effect of community-based rangeland management (CBRLM) on 20 cattle, economic, and rangeland outcomes. Dark and light blue markers denote results 2–3 years after program end (2016, 2017) and dark orange markers denote results 3 years after program end (2017). For each outcome, the mid-point is the standardized treatment effect size with a corresponding 95% confidence interval. Supporting statistical results are shown in Table 4.

members benefitted from participation in a "Small Stock Pass-on Scheme" and a variety of training activities, which are described below.

Rangeland grazing management. The core aim of CBRLM was to shift how communities approached livestock grazing, forage conservation, and risk management by encouraging two key practices: planned grazing and combined herding. Planned grazing entails rotating a community's cattle to a new pasture on a regular basis in accordance with a written plan. The goal was to preserve grass for the dry season and allow grazed pastures more time to recover. Combined herding entails grouping many owners' cattle into one large herd and herding them in a tight bunch. This practice is meant to concentrate animal impact on rangeland, minimize cattle losses, and increase the likelihood that cows are exposed to bulls, thus increasing the pregnancy and calving rates of the entire herd. The scientific and practical rationale behind these practices is reviewed in Supplementary Note 2.

GOPA staff developed grazing plans with each participating community and taught them planned grazing and combined herding via field-based training sessions. These followed a "training of trainers" approach in which GOPA recruited field facilitators from each community, taught them the principles of CBRLM, and tasked them with training their fellow participating pastoralists.

Livestock management. GOPA taught participants some best practices in animal husbandry, including structuring herds to maximize productivity (by increasing the proportion of bulls and reducing the proportion of oxen and cattle over the age of 10 years), providing vaccinations and supplements, and deworming[34]. Additionally, to support the introduction of more bulls into herds, the project implemented a "bull scheme" in which participating communities were given the opportunity to collectively buy certified breeding bulls at a subsidized price. Communities were meant to repay the cost of the bulls either with cash or in-kind trades of goats. Goats collected in this repayment process fed into the small stock pass-on scheme under which participating community members nominated households to receive goats from GOPA. GOPA requested that communities nominate households that owned few or no livestock and were led by youth and/or women. When GOPA received goats as payment for loaned bulls, they would pass them on to nominated households. The recipients were then expected to pass on the offspring of the goats they received to other disadvantaged households.

Cattle marketing. CBRLM also sought to increase participants' marketing of cattle to generate revenue from livestock raising and encourage offtake of unproductive animals[34]. Community facilitators and project experts provided participating herd owners with information about market opportunities and ideal herd composition, and encouraged flexible offtake in response to forage shortages. In 2013, GOPA invested in the development of regional livestock cooperatives that held local auctions and helped farmers transport their animals to markets. Finally, GOPA invested in identifying international export opportunities for CBRLM farmers to Zimbabwe and Angola, although these were generally not successful[31].

Community development. The project sought to institutionalize community-level governance to organize and enforce collective activities like planned grazing, water point maintenance, and financing of livestock inputs. The central management unit of each GA was a new Grazing Area Committee consisting of five to 10 elected community members. The project encouraged participating communities to collectively cover operational expenses in their GA through a GA fund managed by the committee. Among these expenses were the payments to herders, costs of diesel for water pumps and maintenance of water infrastructure, financing collective livestock vaccination campaigns, and any other collective expenses that would support operation of the GA. CBRLM supported every GA fund with a 1:1 matched subsidy. The matched subsidy was limited by a ceiling amount determined by the estimated number of cattle in a GA. GOPA also instructed committees to maintain "GA record books" to track grazing plans, record meeting minutes, and keep logs of community members' participation and financial contributions.

Water infrastructure. GOPA upgraded water infrastructure at a total of 84 sites throughout the NCAs to facilitate planned grazing and combined herding. Water infrastructure improvement included minor upgrades like water tanks and drinking troughs, and larger investments such as the installation of diesel and solar pump systems, the drilling and installation of boreholes, and the construction of pipelines, deep wells, and a large earthen dam[31].

Intervention timeline. The timeline for major components of the research process and CBRLM roll-out is illustrated in Supplementary Fig. 1. The research team conducted the random assignments and the implementation team began community mobilization in early 2010. Formal enrollment in CBRLM began in early 2011. The program implementer conducted mobilization in two waves: they mobilized 11 of 19 RIAs in 2010 and the remaining 8 RIAs in 2011. The evaluation team conducted qualitative data collection to inform the design of social and cattle surveys prior to project end 2014; social surveys in 2014 and 2016; rangeland surveys in the wet and dry seasons of 2016; a cattle survey in 2016; and a household economic survey in 2017.

Cumulative GA-level implementation is illustrated in Supplementary Fig. 2. The project implementer first formally reported enrollment and field visits in April 2011. The implementer achieved nearly full targeted enrollment (50 GAs) by November 11, although some grazing areas were added or subtracted thereafter. Mobilization exceeded enrollment because some grazing area communities chose not to participate in the program and some enrolled in the program and then dropped out. The program averaged between 25 and 50 field visits per month over the project period. A field visit consisted of a week-long community meeting about grazing-plan development and implementation, animal husbandry and budget training, and marketing opportunities.

Randomization. The unit of randomization is the RIA, an intervention zone with a locally recognized boundary. Each RIA falls under the jurisdiction of a single local governing body, known as a Traditional Authority (TA). As noted above, RIAs contain five to 15 GAs where a community of producers share water and forage resources. Grazing areas do not have legally defined boundaries. A herd owner's ability to move among GAs is variable.

GOPA mapped 41 RIAs prior to randomization. Three contiguous RIAs in the north-central region, composed of two treatment RIAs and one control RIA, were omitted from the study post-randomization because reexamination of baseline density of bushland vegetation deemed them unviable for CBRLM implementation. These are the three RIAs without sampled GAs in Fig. 1. The other 38 RIAs were randomly assigned to either receive the CBRLM treatment (19 RIAs) or serve as controls (19 RIAs).

The randomization was stratified by TA to ensure that at least one RIA was assigned to the treatment in each TA. The research team then re-randomized the sample units until seven variables were balanced (a p value of 0.33 or higher for an omnibus f test of all seven variables) between treatment and control: (1) Presence of forest; (2) number of households; (3) number of cattle; (4) cattle density per unit area; (5) quality of water sources; (6) presence of community-based organizations (CBOs); and (7) overlap with complementary interventions (see Supplementary Table 1). For future researchers, we recommend re-randomizing a set number of times and choosing the re-randomization with the highest balance[35]. These variables and indicator variables for TA are included as covariates in all analyses.

Sample selection. In the original sampling strategy, the project implementer was asked to predict the GAs where they would implement the project if the RIA were assigned to treatment. However, there was limited overlap between the GAs that the implementer predicted and the GAs where CBRLM was ultimately implemented. Therefore, the evaluation team devised a revised sampling strategy in 2013, which proceeded in four steps:

Table 4 Treatment effect on rangeland health, cattle productivity, and household economics.

Dependent variable	2–3 years after program end					
	coef.	SE	*p* val.	RI *p* val.	*q* val.	*N*
Panel A: Primary outcomes (indices)						
Herd value	0.00	0.11	0.988	0.994	0.982	653
Herd productivity	0.02	0.09	0.826	0.904	0.982	1285
Weekly household income	0.08	0.07	0.230	0.418	0.975	1210
Weekly household expenditure	0.02	0.05	0.663	0.608	0.975	1210
Household livestock wealth	−0.06	0.05	0.207	0.502	0.975	1210
Panel B: Secondary outcomes (indices)						
Herd structure	−0.02	0.07	0.746	0.841	0.984	653
Time use	0.04	0.10	0.703	0.818	0.984	1210
Resilience	−0.02	0.07	0.786	0.885	0.984	1210
Female empowerment	−0.01	0.08	0.880	0.909	0.984	1210
Meat and dairy consumption	0.00	0.04	0.990	0.993	0.997	1210
Panel C: Rangeland outcomes (standardized)						
Erosion:						
Wet season site erosion (1 = no erosion, 0 = erosion)	−0.08	0.10	0.389	0.661	.	972
Ground cover						
Wet season unexposed soil surface (%, logit-transformed)	−0.21	0.10	0.051	0.160	.	972
Wet season plant litter cover (%, logit-transformed)	−0.18	0.08	0.035	0.201	.	972
Dry season plant litter cover (%, logit-transformed)	−0.09	0.12	0.444	0.715	.	885
Herbaceous cover						
Wet season herbaceous canopy cover (%, logit-transformed)	−0.26	0.14	0.072	0.270	.	972
Dry season herbaceous canopy cover (%, logit-transformed)	−0.23	0.07	0.002	0.079	.	885
Wet season fresh plant biomass at site (kg/ha, log-transformed)	−0.26	0.16	0.104	0.294	.	966
Dry season fresh plant biomass at site (kg/ha, log-transformed)	−0.21	0.07	0.004	0.112	.	792
Relative canopy cover of perennial and annual grasses						
Wet season perennial to annual canopy ratio (log-transformed)	−0.05	0.08	0.486	0.750	.	972
Relative canopy cover of grasses and forbs						
Wet season grass to forb canopy ratio (log-transformed)	−0.23	0.10	0.025	0.260	.	972
Weeds						
Wet season % of shrubs that are not stinkbush (%, logit-transformed)	0.02	0.08	0.770	0.922	.	870
Wet season grass to Aristida canopy cover ratio (log-transformed)*	−0.14	0.13	0.259	0.467	.	752
Woody vegetation						
Wet season shrub canopy cover (%, logit-transformed)	−0.01	0.14	0.956	0.972	.	972
Dry season shrub canopy cover (%, logit-transformed)	−0.09	0.15	0.569	0.734	.	885

Notes: Each coef. is the coefficient on the treatment variable in an OLS regression of a physical program outcome on treatment status. It is an intent-to-treat (ITT) estimate relative to the control group. Data in Panels A and B were collected from surveys of heads of household and cattle managers, and data in Panel C were collected from randomly selected transects as described in the Methods. Standard errors are clustered at the RIA level, i.e., the unit of randomization. RI *p* values are calculated using randomization inference. Each regression includes as controls a categorical variable for traditional authority (an administrative unit) that was used for block stratification and the RIA-level variables used in re-randomization to ensure balance, which are: quality of water source, an indicator for whether the RIA has a community based organization, vegetation type, number of livestock, livestock density, the log of the number of CBRLM-eligible households, and an indicator for whether the RIA overlaps with prior intervention areas. Indices are the standardized (mean = 0 and sd = 1), unweighted average of standardized components. Monetary variables have been scaled to weekly Namibian dollar (NAD) amounts. At the time of data collection (2017) the exchange rate was 13.3 NAD to 1 USD. Rangeland outcomes have been transformed as noted in parentheses to better meet assumptions of normality and homogeneity of variance. See "Materials and Methods" and the Supplementary Materials for details of index and variable construction. Multiple hypothesis correction was not specified for rangeland outcomes in the pre-analysis plan. All *p* values are two-tailed.
*Aristida is a genus of grasses that are undesirable forage plants in this context.

1. Map GAs in sampled RIAs: The evaluation team traveled to all 38 RIAs and worked with TAs and Namibian Agricultural Extension (AE) officers to map all the GAs in each RIA. The team mapped 171 GAs in control RIAs and 213 GAs in treatment RIAs.
2. Collect pre-program data on GAs: The evaluation team collected information on pre-program characteristics of each GA from interviews with TAs and AE staff, the Namibian national census[36], and the Namibian Atlas[37]. The latter has a geo-referenced database on climate, ecology, and livestock for the nation.
3. Predict CBRLM enrollment for treatment GAs: The researchers used these data in a logistic regression to predict the probability that each GA would enroll in CBRLM and would adopt the CBRLM interventions based on pre-program characteristics. For example, the model found that GAs with more existing water infrastructure, strong social cohesion, and adequate cell phone service were more likely to be enrolled in the program. The variables used to predict CBRLM adoption were: (1) Presence of water installations (yes/no); (2) carrying capacity of the land (above/below the regional median); (3) community's readiness to change (high/very high); (4) community's social cohesion (high/very high); (5) spillover effects from neighbors; (6) quality of herders and herder turnover; (7) presence of members of the Himba ethnic group; (8) the TA's readiness to change; (9) cell phone coverage; and (10) primary housing material (mud, clay, or brick).
4. Generate sample of GAs in treatment and control RIAs: The evaluation team applied the statistical model (above) to all GAs in the sample and set a cut-off point to separate GAs that were likely to adopt the CBRLM program vs. those that were unlikely to do so. In treatment RIAs, the model predicted 52 GAs, of which 37 were formally enrolled in CBRLM and 15 were not. In control RIAs, 71 GAs met or exceeded the cutoff; they offer the best counter-factual estimate of which GAs would have enrolled in the program had their RIA received treatment.

Data collection. The names, survey questions, and variable constructions for all outcomes included in the analysis are available at the AEA RCT Registry (ID number: AEARCTR-0002723). See Supplementary Methods for a list of definitions of variables depicted in Fig. 2 and 3.

Social surveys. Social surveys were intended to assess the effect of CBRLM on community behaviors, community dynamics, knowledge, and attitudes. All data were collected using electronic tablets with the SurveyCTO software[38].

The primary unit of analysis for household respondents is the manager of the cattle kraal (holding pen). Researchers conducted surveys with kraal managers,

Table 5 Treatment effect on indices of rangeland health, cattle productivity and household economics, and their components (Panel A).

Panel A: Primary outcomes	2–3 years after program end					
Dependent variable	**coef.**	**SE**	***p* val.**	**RI *p* val.**	**Ctrl mean**	***N***
Index: Herd value	0.00	0.11	0.988	0.994	0.00	653
Total number of cattle per kraal	0.23	3.61	0.950	0.971	34.15	653
Total meat production per kraal (kg)	−33	1083	0.976	0.984	9010	653
Total herd market value (NAD)	−8953	116,241	0.939	0.960	1007,571	653
Index: Herd productivity	0.02	0.09	0.826	0.904	0.00	1285
Calving rate among productive calves	0.00	0.03	0.940	0.961	0.74	641
Change in herd size (# of cattle, rainy season)	0.47	1.27	0.715	0.780	−8.23	1243
Weekly milk products produced (kg, rainy season)	4.71	6.55	0.477	0.578	26.06	1153
Sub-index: Cattle weight	−0.06	0.09	0.480	0.622	0.00	653
Average cow weight (kg)	0.13	4.96	0.978	0.987	299.60	641
Average ox weight (kg)	4.66	7.25	0.524	0.623	380.38	587
Average male calf weight (kg)	1.95	2.36	0.415	0.724	118.65	564
Average female calf weight (kg)	−2.17	2.58	0.407	0.580	116.84	578
Average heifer weight (kg)	−6.68	4.47	0.144	0.323	245.58	576
Average steer weight (kg)	−11.15	6.04	0.073	0.271	241.01	363
Average bull weight (kg)	16.11	12.59	0.209	0.343	386.04	361
Sub-index: Cattle body condition	−0.31	0.21	0.145	0.463	0.00	653
Average cow body condition (0–5 scale)	−0.12	0.08	0.139	0.450	0.44	641
Average ox body condition (0–5 scale)	−0.15	0.11	0.195	0.520	0.98	587
Average male calf body condition (0–5 scale)	−0.04	0.05	0.437	0.711	0.27	564
Average female calf body condition (0–5 scale)	−0.10	0.06	0.072	0.354	0.26	577
Average heifer body condition (0–5 scale)	−0.19	0.11	0.090	0.385	0.65	576
Average steer body condition (0–5 scale)	−0.28	0.11	0.013	0.232	0.69	364
Average bull body condition (0–5 scale)	−0.09	0.15	0.539	0.705	1.03	362
Additive index: Weekly per capita household income (NAD)	39.81	32.59	0.230	0.418	201.09	1210
Total crop revenue (NAD, scaled from 12 months)	2.76	2.43	0.263	0.393	4.32	1210
Total formal employment profits (NAD, scaled from 12 months)	43.53	67.14	0.521	0.738	340.82	1210
Total value of all food produced at home (NAD, weekly)	−2.80	33.72	0.934	0.970	201.48	1210
Total value of non-sold byproducts (NAD, weekly)	−0.04	0.05	0.349	0.349	0.19	1210
Value of own cattle used for plowing (NAD, scaled from 12 months)	−2.35	3.27	0.477	0.641	33.15	1195
Total cattle sale revenue (NAD, scaled from 12 months)	6.24	27.83	0.824	0.881	79.24	1210
Total cattle byproduct sale revenue (NAD, scaled from 12 months)	0.48	0.51	0.354	0.679	1.94	1210
Amount of remittances received (NAD, scaled from 12 months)	4.73	2.29	0.046	0.237	15.20	1172
Additive index: Weekly per capita household expenditure (NAD)	28.66	65.17	0.663	0.608	402.70	1210
Total amount borrowed (NAD, scaled from 12 months)	−46.94	24.29	0.061	0.373	77.25	1210
Total nonfood expenditure (NAD, scaled from 12 months)	−40.91	74.52	0.586	0.743	306.23	1210
Total nonfood expenditure (NAD, scaled from 30 days)	125.20	61.57	0.049	0.144	426.57	1210
Total crop expenditure (NAD, scaled from 12 months)	0.54	0.40	0.181	0.495	3.32	1183
Expenditure hiring animals for plowing (NAD, scaled from 12 months)	0.09	0.22	0.691	0.826	1.20	1210
Amount sent in remittances (NAD, scaled from 12 months)	5.06	3.67	0.176	0.432	21.89	1210
Total expenditure on water (NAD, scaled from 12 months)	0.08	0.91	0.927	0.967	6.60	1176
Total value of food purchased (NAD)	4.67	90.06	0.959	0.970	314.33	1210
Amount spent purchasing cattle (NAD, scaled from 12 months)	0.54	6.89	0.938	0.972	29.93	1210
Amount spent transporting sold cattle (NAD, scaled from 12 months)	0.07	0.13	0.620	0.654	0.13	1210
Total cattle upkeep expenditure (NAD, scaled from 12 months)	9.90	20.99	0.640	0.817	176.18	1210
Index: Household livestock wealth	−0.06	0.05	0.207	0.502	0.00	1210
Total cattle wealth (livestock units)	−4.40	3.13	0.168	0.391	30.62	1176
Total non-cattle wealth (livestock units)	−0.07	0.49	0.885	0.935	6.35	1210

Notes: See Table 4 notes for details on regression specification. Herd value, herd productivity, and household livestock wealth indices are the standardized (mean = 0 and sd = 1), unweighted average of the standardized components listed below each index. Income and expenditure indices are the sum of components, adjusted for household size. See "Methods" for a complete description of index creation. Monetary variables are in Namibian dollar (NAD) amounts. 0–1 years after program end (2014), the exchange rate was 10.8 NAD to 1 USD, and 2–3 years after program end was 14.7 NAD to 1 USD. Cattle body condition scores are on a 0–5 scale used by Meat Corporation of Namibia, with 0 being low fat content and 5 being high. Component variables without description of units are binary, with positive responses coded as 1. All *p* values are two-tailed.

rather than heads of households, for three reasons. First, many kraals contain cattle owned by multiple households, and decisions about grazing practices, cattle treatment, and participation in grazing groups are generally made at the kraal level. Second, many cattle-owning households do not directly oversee the day-to-day activities of their cattle (many live outside the GA), and so would be unable to answer questions about key outcomes, such as livestock management behaviors and community dynamics[39]. Finally, enrollment in CBRLM occurred at the kraal, rather than household, level.

In 2014, the research team worked with local headmen and other community members to generate a complete census of kraals in every sampled Grazing Area

Table 6 Treatment effect on indices of rangeland health, cattle productivity and household economics, and their components (Panel B & C).

Dependent variable	2–3 years after program end					
	coef.	SE	*p* val.	RI *p* val.	Ctrl mean	*N*
Panel B: Secondary outcomes						
Index: Herd structure	−0.02	0.07	0.746	0.841	0.00	653
Ratio of bulls to cows is higher than 1:40	−0.10	0.03	0.001	0.104	0.61	646
(−1)*Ratio of oxen to total cattle	0.01	0.01	0.649	0.742	−0.15	653
(−1)*Ratio of unproductive cattle to total cattle	0.02	0.01	0.206	0.586	−0.13	653
Index: Time use	0.04	0.10	0.703	0.818	0.00	1210
Days spent herding (typical week scaled to annual, adult)	−8.40	10.49	0.429	0.558	81.70	1210
Days spent working on crops (past year, adult)	2.91	2.37	0.228	0.460	0.88	1210
Days formally employed (past year, adult)	3.62	4.57	0.433	0.586	34.74	1210
(−1)*Days spent herding (typical week scaled to annual, child)	−2.76	4.50	0.543	0.680	−15.43	970
(−1)*Days spent working on crops (past year, child)	−0.27	0.30	0.381	0.594	−0.17	970
(−1)*Days formally employed (past year, child)	−0.24	0.33	0.461	0.773	−0.22	970
Index: Resilience	−0.02	0.07	0.786	0.885	0.00	1210
FAO food security index (−3–0; −3 = severely insecure)	−0.12	0.09	0.205	0.572	−1.62	1207
Did not lack money for school fees (past year)	0.02	0.02	0.343	0.622	0.89	1210
Savings available to cover emergency expense (NAD)	−31.05	211.14	0.884	0.929	1,486	1210
Savings and credit available to cover emergency expense (NAD)	−341.20	216.17	0.123	0.407	2,829	1210
Household saves money	0.04	0.05	0.390	0.636	0.70	1165
Total household savings (NAD)	−1189	2,279	0.605	0.731	6,720	1034
Index: Female empowerment	−0.01	0.08	0.880	0.909	0.00	1210
Any female HH member owns cattle	−0.03	0.04	0.382	0.597	0.48	1210
Fraction of HH cattle owned by women	−0.01	0.03	0.681	0.798	0.25	1111
Any new female goat owner in HH (past 3 years)	0.02	0.02	0.457	0.616	0.13	1210
Index: Meat and dairy consumption	0.00	0.04	0.990	0.993	0.00	1210
Per capita meat consumption (kg, past week)	−1.12	2.00	0.579	0.684	6.77	1210
Per capita dairy consumption (kg, past week)	0.09	0.31	0.763	0.868	1.15	1197
Panel C: Rangeland outcomes						
Erosion						
Wet season site erosion (1 = no erosion, 0 = erosion)	−0.04	0.05	0.389	0.661	0.517	972
Ground cover						
Wet season protected soil surface (%, logit-transformed)	−0.34	0.17	0.051	0.160	0.807	972
Wet season plant litter cover (%, logit-transformed)	−0.22	0.10	0.035	0.201	0.547	972
Dry season plant litter cover (%, logit-transformed)	−0.18	0.23	0.444	0.715	0.620	885
Herbaceous cover						
Wet season herbaceous canopy cover (%, logit-transformed)	−0.53	0.29	0.072	0.270	0.446	972
Dry season herbaceous canopy cover (%, logit-transformed)	−0.52	0.16	0.002	0.079	0.216	885
Wet season fresh plant biomass at site (kg/ha, log-transformed)	−0.45	0.27	0.104	0.294	459	966
Dry season fresh plant biomass at site (kg/ha, log-transformed)	−0.48	0.16	0.004	0.112	233	792
Relative canopy cover of perennial and annual grasses						
Wet season perennial to annual canopy ratio (log-transformed)	−0.18	0.26	0.486	0.750	22.800	972
Relative canopy cover of grasses and forbs						
Wet season grass to forb canopy ratio (log-transformed)	−0.33	0.14	0.025	0.260	43.329	972
Weeds						
Wet season % of shrubs that are not stinkbush (%, logit-transformed)	0.02	0.07	0.770	0.922	0.991	0.964
Wet season grass to Aristida canopy cover ratio (log-transformed)*	−0.18	0.16	0.259	0.467	12.962	12.935
Woody vegetation						
Wet season shrub canopy cover (%, logit-transformed)	−0.01	0.19	0.956	0.972	0.084	972
Dry season shrub canopy cover (%, logit-transformed)	−0.13	0.23	0.569	0.734	0.108	885

Notes: See Table 4 notes for details on regression specification. Each index is the standardized (mean = 0 and sd = 1), unweighted average of the standardized components listed below it; see "Materials and Methods" for a complete description of index creation. Monetary variables are in Namibian dollar (NAD) amounts. 0–1 years after program end (2014), the exchange rate was 10.8 NAD to 1 USD, and 2–3 years after program end was 14.7 NAD to 1 USD. Component variables without description of units are binary, with positive responses coded as 1. Rangeland outcomes have been transformed (but not standardized as in Table 2) as noted in parentheses to better meet assumptions of normality and homogeneity of variance; treatment and control means are sample means computed from data on untransformed scales. All *p* values are two-tailed.
*Aristida is a genus of grasses that are undesirable forage plants in this context.

(GA) that contained 10 or more cattle at the start of the program (an eligibility requirement for enrollment in CBRLM). The research team randomly sampled up to 11 community members for participation in the 2014 kraal manager survey. Surveys were conducted in the manager's local language and lasted ~45 min. Alongside the 2014 survey, teams of two surveyors visited all grazing areas where at least one respondent reported participating in a community grazing group or community combined herd to corroborate reported behaviors through direct observation.

To assess the persistence of CBRLM's effects on behaviors, community dynamics, knowledge, and attitudes, the research team conducted a follow-up survey of kraal managers in 2016, two years after program end. The survey team randomly sampled two additional kraals in each grazing area to account for the

Table 7 Mechanisms.

Dependent variable	Treatment effect 2 years after program end					
	coef.	SE	*p* val.	RI *p* val.	Ctrl mean	*N*
Panel A: Direct evidence of grazing intensity						
Evidence of heavy grazing on herbaceous plants (wet season)	0.12	0.04	0.003	0.032	0.13	972
Evidence of heavy grazing on herbaceous plants (dry season)	0.10	0.04	0.016	0.106	0.46	972
Evidence of any grazing on herbaceous plants (wet season)	0.04	0.03	0.151	0.336	0.92	972
Evidence of any grazing on herbaceous plants (dry season)	0.00	0.03	0.953	0.980	0.87	972
Panel B: Potential causes of increased grazing intensity						
Cattle numbers						
Number of herds currently in GA	−1.49	1.80	0.413	0.580	21.94	1210
Number of cattle currently in GA	−178	130	0.178	0.433	1011	1245
Reduced farmer movement						
Manager moved cattle outside GA in past year	−0.04	0.03	0.290	0.549	0.20	1242
Fraction of herd that manager moved outside GA in past year	−0.04	0.04	0.295	0.567	0.19	1238
Number of months in which manager moved cattle outside GA (past 12 months)	−0.19	0.17	0.273	0.535	0.92	1243
Number of years in which manager moved cattle outside GA (past 6 years)	−0.08	0.16	0.636	0.782	0.76	1243
Outside encroachment						
Outside farmers brought cattle to GA in past year	0.05	0.03	0.105	0.408	0.37	1207
Outside farmers brought cattle to GA in past year without permission	0.07	0.02	0.005	0.070	0.16	1230
Freq. at which herders saw outside herders in GA in past wet season (1–6 scale)	0.15	0.30	0.617	0.785	2.69	280
Freq. at which herders saw outside herders in GA in past dry season (1–6 scale)	0.40	0.27	0.151	0.241	2.77	277
Herders saw outside herder in GA more than once a week in past wet season	0.07	0.07	0.326	0.550	0.28	280
Herders saw outside herder in GA more than once a week in past dry season	0.13	0.07	0.056	0.196	0.31	277

Notes: Each coef. is the coefficient on the treatment variable in an OLS regression of a program outcome on treatment status. It is an intent-to-treat (ITT) estimate relative to the control group. Standard errors are clustered at the RIA level, i.e., the unit of randomization. RI *p* values are calculated using randomization inference. Each regression includes as controls a categorical variable for traditional authority (an administrative unit) that was used for block stratification and the RIA-level variables used in re-randomization to ensure balance, which are: vegetation type, number of livestock, livestock density, the log of the number of CBRLM-eligible households, and binary indicators for whether the RIA overlaps with prior intervention areas, has a quality water source, and has a community based organization. The 1–6 scale used to measure frequency at which herders saw outside herders in the GA is as follows: 0 = "never", 1 = "less than once a month", 2 = "once a month", 3 = "multiple times per month", 4 = "once a week", 5 = "multiple times per week", 6 = "daily". Variables without description of units are binary. All *p* values are two-tailed.

possibility of attrition. The 2016 survey lasted approximately one hour on average, and included an expanded list of questions about governance, social conflict, and collective action as well as new survey modules on cattle marketing, cattle movement, and livestock management. In 2017, the research team randomly sampled three kraals in each grazing area to conduct direct observation audits of key rangeland grazing-management behaviors.

To assess the effects of CBRLM on economic outcomes, the research team conducted a household-level survey in 2017, three years after program end. The survey instrument asked detailed questions on topics that could not be answered by kraal managers, such as household consumption, income, food security, and savings. To select households for this survey, during the 2016 survey the research team asked kraal managers to list all households that owned cattle in the manager's kraal, then randomly selected one household from each kraal. Alongside the 2017 survey, the research team conducted an in-depth survey with the local headman of all 123 GAs in the sample. The headman survey focused on historical background about the grazing area, as well as the headman's perceptions of rangeland and livestock issues.

Cattle data. The cattle component was intended to assess effects of CBRLM on cattle numbers, body condition, and productivity. The variables of key interest involved the average liveweight and body condition, calving rates, and average market value of cattle, as well as overall herd structures.

The data collection protocols closely followed standards from livestock assessments elsewhere in Sub-Saharan Africa[40]. The research team randomly selected up to six kraals in each GA to participate in the cattle survey. The survey team mobilized selected herds during multiple community visits to ensure all herds were accounted for. Herd owners were compensated for the costs of rounding up animals and weighed cattle received anti-parasite treatment ("dipping")[41]. A total of 19,875 cattle from 669 herds were weighed.

The data-collection process for each herd proceeded in six steps. First, surveyors worked with herd managers to round up all cattle that regularly stayed in the selected cattle kraal. Once cattle had been brought to the designated location for data collection, they were passed through a mobile crush pen and scale. As each animal passed through the crush pen, a survey team member recorded the animal type (i.e., bull, ox, cow, calf) and used a SurveyCTO randomizer to calculate whether the animal was randomly selected for assessment. The random number generator was set to randomly select approximately 30 cattle from each herd for weighing. If the animal was selected, the survey team kept the animal on the scale and recorded its weight and body condition. A semi-subjective 1–5 scale, commonly used by livestock buyers in the NCAs (see Supplementary Fig. 3), was adjusted to a 0–4 scale used to determine formal market pricing. The team then placed the animal in a neck clamp and estimated the animal's age by dentition (but extremely young calves were aged visually). Each animal was marked as it moved through the crush pen to ensure that it was assessed only once. In addition to assessing randomly selected animals, the survey team weighed and aged all bulls in the herd. The cattle survey yielded average cattle weight, age, and body condition for 19,875 animals across all treatment and control GAs, as well as estimates of calving rates, ratios of bulls to cows, and ratios of productive to unproductive animals.

Rangeland data. The rangeland ecology research was intended to assess treatment effects on vegetation and soil surface conditions. Full research details, including field technician training protocols, are available elsewhere[42]. The data collection approach followed methods commonly used in Africa[43,44]. Extended definitions of variables depicted in Fig. 3 and Table 2 are available in the "Supplementary Methods" section.

The rationale for how the ecological variables presented in Fig. 3 translate into assessments of rangeland condition or health is based on forage and soil characteristics from a livestock production perspective[25]. The highest quality forages for cattle on rangelands are perennial grasses, since annual grasses are more ephemeral in terms of nutritive value and productivity. Herbaceous forbs often have the poorest forage quality for large grazers because of their low fiber content and risks of containing toxic chemicals. When rangelands are degraded by overgrazing, perennial grasses are reduced and replaced by annual grasses and forbs. This trend reflects animal diet selectivity that favors consumption of the perennial plants. Reversing such trends via management interventions can be difficult. The main option is to reduce grazing pressure and hope that perennial grasses can outcompete annuals and become reestablished over time. Another option is to implement a grazing rotation that allows perennial grasses to recover after a grazing period.

Increases in annual grasses are documented to occur as one outcome of chronic overgrazing in Namibia[45,46]. In 2016, annual grasses were 5-times more abundant than perennial grasses in our study area. When over-grazing occurs, most plant material is harvested and less is available for the pool of organic matter (OM) for the topsoil. Less OM (e.g., plant litter) on the soil surface means that more soil is also exposed to wind and rain, accelerating erosion. The GAs in our research occur on various soil types and landscapes, some of which are more susceptible to erosion than others. Silty soils on slopes are vulnerable to erosion, for example, while sandy soils on level sites are less vulnerable[25].

On-the-ground sampling was conducted in all 123 selected GAs along an 800-km zone running West to East. Elevations ranged from 750 to 1700 masl (West) and 1050 to 1120 masl (East). Within each sampled GA, up to 12 1-ha (square) sampling sites were initially chosen using coordinates generated randomly from latitude and longitude coordinates in a satellite image of the GA[47]. About 17% of sites were later removed from the sample based on their close proximity to landscape disturbances or inaccessibility by field technicians. Overall, 972 sites were analyzed in the wet season and 885 in the dry season of 2016, two years after the implementation phase of CBRLM had ended.

The geographic center-point for a sampling site was generated using a spatially constrained random distribution algorithm applied to the satellite image, and the field team navigated to the center-point coordinates using GPS technology. The team took photographs and recorded descriptive information including elevation, slope, aspect, other landscape features, vegetation type, dominant plant species, soil type, soil erosion, and degree of grazing or browsing pressure, and proximity to high impact areas such as trails, water points, and villages.

At the center point, the survey team then established two perpendicular transects, each 100 m in length and crossing at the middle. The resulting four, 50-m transect lines ran according to each cardinal direction (N, S, E, W) as determined with a compass. Technicians then placed 1-m notched sampling sticks at randomized locations along each transect line and recorded what plants or other materials (i.e., stone, wood, leaf litter, animal dung, etc.) were located under or above the notches of the sampling sticks. These data points were tabulated to calculate percent cover for various categories of vegetation; there were $n = 200$ data points per site based on 40 stick placements and 5 notches per stick. This method enabled precise calculation of cover values for herbaceous (i.e., grass, forb) and diminutive woody plants (i.e., small shrubs, seedlings, saplings, etc.). Tree cover was estimated from point data collected via a small adjustment in the approach[42]. Herbaceous species were identified in wet seasons but not in dry seasons due to senescence during the latter.

Quadrat sampling supplemented the notched stick approach. Random placements of a 1-m^2 quadrat frame within the sampling site allowed for 20 estimates of a soil surface condition score ranging from 1 (poor) to 2 (moderate) or 3 (good)[42]. Poor was indicated by smooth soil surfaces, absence of litter, having poor infiltration and signs of erosion such as rills, pedestals, or terracettes; good was indicated by rough soil surfaces, abundant litter, seedlings evident, and lack of evidence of erosion. Herbaceous biomass was estimated in the quadrats and weighed to estimate herbaceous biomass.

Statistics

Index creation. Index construction for socioeconomic variables was composed of several steps[48]. For each response variable we first signed all component variables such that a higher sign is a positive outcome, i.e., in line with CBRLM's intended impacts. Then we standardized each component by subtracting its control group mean and dividing by its control group standard deviation. We computed the mean of the standardized components of the index and standardized the sum once again by the control group sum's mean and standard deviation. When the value of one component in an index was missing, we computed the index average from the remaining components. See Tables 3–6 for index components.

Calculation of average treatment effects. The estimate of interest is the Average Treatment Effect (ATE), or the average change in an outcome generated by assignment to CBRLM. We estimate the ATE using standard Ordinary Least Squares regression and control for variables used in stratification. Regressions for rangeland outcome variables include a unique set of controls, including rainfall over the project period, rainfall in the year of data collection, grazing area cattle density, grazing area ecological zones, and a remote-sensing estimate of pre-project biomass. The core model takes the form:

$$\hat{Y} = \alpha + \beta_1 T + \boldsymbol{\beta}\mathbf{X} \quad (1)$$

where T represents treatment assignment and $\mathbf{X}$ represents pre-treatment covariates used to test for balance during re-randomizations. The results capture the intention-to-treat (ITT) effect rather than the effect of treatment-on-treated (TOT). ITT is more appropriate than TOT in this context for two principal reasons. First, it is more relevant for policymakers – the effect of policies should account for imperfect compliance. Second, "uptake" is not well-defined, and certainly not a binary concept, for CBRLM since many communities and community members complied partially, complied with some but not all components, and complied for some but not all of the time.

Standard errors and p *values*. We report two-tailed p values for all analyses. For each outcome, we show the two-tailed p value from a standard Ordinary Least Squares (OLS) regression with standard errors clustered at the level of the RIA, the unit of randomization[49]. We also calculate two-tailed p values using Randomization Inference (RI). To calculate RI p values, we re-run the randomization procedure (described above) 10,000 times and generate an Average Treatment Effect (ATE) under each hypothetical randomization. The p value is the percent of re-randomizations that generate a treatment effect that is either equal to, or larger in absolute value than, the true ATE.

Multiple hypotheses correction. We calculate q values to account for families of outcome indices with multiple hypotheses[50]. The q value represents the minimum false discovery rate at which the null hypothesis would be rejected for a given test. We pre-specified five families of indices:

1. Behavioral outcomes (all in 2014): Grazing planning, Grazing-plan adherence, Herding practices, and Herder management.
2. Behavioral outcomes (all in 2016): Grazing planning, Grazing-plan adherence, Herding practices, and Herder management.
3. Primary material outcomes: Cattle herd value (2016), Herd productivity (2016), Household income (2017), Household expenditures (2017), Household livestock wealth (2017).
4. Secondary material outcomes: Time use (2017), Resilience (2017), Female empowerment (2017), Diet (2017), and Herd structure (2016).
5. Mechanisms: Collective Action (2014, 2016), Community Governance (2014, 2016), Community disputes (2014, 2016), Trust (2014), Self and community efficacy (2014, 2017), and Knowledge (2016).

Heterogeneous treatment effects analysis. We are interested in whether the effect of CBRLM was impacted by lower rainfall in some grazing areas during the project period. We evaluated heterogeneous treatment effects by rainfall in grazing areas using a variety of measures of rainfall, including aggregate rainfall during the project period and deviation in aggregate rainfall from the ten-year mean during the project period.

For simplicity, Supplementary Tables 5 and 6 present the results of analysis of the interaction between treatment and a binary indicator of low rainfall. To construct this indicator, for each GA we first compute the absolute difference between mean rainfall during the project and mean rainfall during the 10 years prior (2000–2010). We divide the absolute difference by mean rainfall during the 10 years prior to produce a relative (%) difference. We then determine the median relative difference over all GAs. For each GA, we assign the value 1 to the low rainfall indicator if the relative difference for the GA is less than the median relative difference over all GAs; we assign 0 otherwise. The results are consistent when we use alternative rainfall measures.

Spillovers analysis. Because CBRLM grazing areas were more likely to experience external incursions by cattle herds from outside the community, we test for spillovers. Specifically, we are interested in whether control grazing areas near treatment areas were affected by having a treatment grazing area nearby. We conducted the spillovers analysis only on control group grazing areas. For each control group grazing area, we measured the distance to the border of the nearest treatment grazing area. We created a binary measure taking the value 1 if the distance between the control group grazing area and nearest treatment group grazing area is below the median distance, and 0 otherwise. We find no evidence of spillover effects. The results are presented in Supplementary Table 7.

Ethical considerations. Approval for this study was obtained from the Institutional Review Boards at Yale University (1103008148), Innovations for Poverty Action (253.11March-001), and Northwestern University (STU00205556-CR0001). The program was conceived, designed, and implemented by the Millennium Challenge Account compact between the Millennium Challenge Corporation and the Government of Namibia. The research team did not participate in program design or implementation. Communities and individual farmers were informed that they were free to withdraw from participation in evaluation activities at any time. The random assignment of the program was appropriate given the uncertainty around the program's effect, and the Government of Namibia committed to implementing the program in control areas if the evaluation showed positive results.

The research team took a number of steps to ensure the autonomy and well-being of study participants. First, we designed the survey and data collection protocols after considerable qualitative field work to ensure that questions about sensitive issues (e.g., cattle wealth, cattle losses, attitudes towards the Traditional Authority) were phrased appropriately and did not engender adverse emotional or social consequences. Second, all survey activities were reviewed and approved by the MCA compact, Regional Governors, and Traditional Authorities. Third, surveys were conducted with informed consent and in private to ensure that information remained private and respondents were as comfortable as possible during the survey. Finally, the research team disseminated findings on market prices and rangeland condition to communities and regional Agriculture Extension Officers.

We received no negative reports about the community reception of the survey from surveyors during the evaluation. Two cows were injured during the cattle weighing exercise, and the owner was financially compensated in line with a compensation agreement made with all farmers prior to the cattle weighing exercise.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

Hypotheses and analytical methods for this research were pre-registered prior to analysis through the American Economic Association's RCT registry and are available online (https://www.socialscienceregistry.org/trials/2723). Data used for this research are accessible at the Millennium Challenge Corporation website (https://data.mcc.gov/evaluations/index.php/catalog/138/study-description) and will also be linked to on the Innovations for Poverty Action dataverse. In the publicly available data, some numerical outliers have been censored in order to preserve the anonymity of the survey respondents. This censoring does not affect the direction and statistical significance of our results. Access to uncensored data is available upon request from the Millennium Challenge Corporation or the corresponding author, subject to approval by the Millennium Challenge Corporation.

Code availability

Data analysis was conducted in R and Stata. All code needed to replicate the figures and tables in this paper and the Supplementary Information is available, with accompanying datasets, through the Millennium Challenge Corporation at (https://data.mcc.gov/evaluations/index.php/catalog/138/study-description) and will also be linked to on the Innovations for Poverty Action dataverse.

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Competing interests

The authors declare no competing interests.

Additional information

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