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Strong collaborative governance networks support effective Forest Stewardship Council-certified community-based forest management: Evidence from Southeast Tanzania

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ABSTRACT

Research on community-based forest management indicates its conservation outcomes depend on local rule enforcement, extraction pressures, and community support. However, many community-based forest management projects, particularly in the Global South, also involve collaborative networks of non-state actors such as NGOs and private corporations. Many of these networks promote sustainability certification under programs like the Forest Stewardship Council. We report on analyses of longitudinal forest cover data constructed using satellite observations alongside inter-organizational collaborative governance network data constructed from archival sources, document analysis, and oral histories to assess how collaborative governance networks shape community-based forestry's conservation effectiveness in eight villages in Kilwa District, Tanzania. Our findings indicate certified community-based forestry's impacts on deforestation can depend on the composition and structure of collaborative governance networks. Using matched Cox proportional hazards models with geographic fixed effects, we find evidence that certified community-based forest management can stem forest loss as effectively as state-led forest management (in the form of National Forest Reserves). However, the characteristics of collaborative governance networks connecting organizations engaged in forest management in our study villages shape both which areas are selected into certified community-based forest management and villages' overall deforestation rates. Specifically, we find that the more each village government's organizational partners are connected to one another through bonding ties, and the more civil society organizations collaborate with each village government through bridging ties, the lower the village's deforestation risk. More private sector organizations connected to village governments through bridging ties, however, are associated with higher deforestation risks. Our evidence highlights the importance of investments in inter-organizational networks for promoting sustainably certified community-based forest conservation.

1. Introduction

Deforestation threatens biodiversity (Alroy, 2017), contributes to global warming (Hu et al., 2021), and undermines timber and non-timber forest products' substantial household livelihood contributions (Angelsen et al., 2014; Fedele et al., 2021). With the recent Kunming-Montreal Global Biodiversity Framework aspiring to bring 30% of Earth's terrestrial area under "effective area-based conservation measures" (Target 3), debates about how to support both non-human species and human livelihoods while conserving landscapes are ever more important (Büscher et al., 2017; Crist et al., 2021; Pimm et al., 2018; Wilson, 2016; Zeng et al., 2022).

One growing set of experiments intended to reconcile these tensions goes by several names, including community-based forest management,

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[1] The preparation of this paper has been overshadowed by Dr. Asubisye Mwamfupe's sudden death. What a brilliant, loving man he was. In sorrow, we dedicate this work to his memory.

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participatory forest management, and social forestry, among others. While these approaches have some differences, they all incorporate local communities in collective forest management (Maraseni et al., 2019; van Noordwijk, 2020; Tole, 2010; Wong et al., 2020). These experiments, which for simplicity we refer to as community-based forest management, began amid a turn away from top-down policies focused on forest control and extraction. We refer to these more traditional approaches, encompassing strategies like national parks or forest reserves, as state-led forest management. In the Global South, they were commonly instituted by colonial administrations and retained or reinstated by postcolonial governments.

During the 2000s, in part to strengthen the environmental benefits of community-based forest management, NGOs and development agencies started promoting standards for sustainability certification (Humphries and Kainer, 2006; De Pourcq et al., 2009; Wiersum et al., 2013; Kalonga et al., 2015). The Forest Stewardship Council (FSC) certification system became particularly prominent in this effort, in part fueled by global and local conservation NGOs' efforts simultaneously to promote sustainable forestry in the Global South and link local communities to international forest product markets (Pattberg, 2006; Chan and Pattberg, 2008; Frey et al., 2022).

FSC certification is costly and technically demanding to attain. Interested NGOs often support certification by raising funds and brokering ties between local community governments and broader inter-organizational networks of stakeholders. Previous research on community-based forestry provides substantial evidence that its effectiveness depends on contextual factors such as rule enforcement, extraction pressures, and community support (Angelsen et al., 2014; Baragwanath and Bayi, 2020; Fedele et al., 2021; Hajjar et al., 2021; Lund et al., 2018; Samij et al., 2014). The complex interactions between local governments, civil society, and private sector organizations found in many cases of certified community-based forest management can be understood as a form of collaborative governance, where local resource users work to resolve resource management problems in cooperation with other concerned organizations (Schoon et al., 2017; see also Ansell and Gash, 2008; Emerson et al., 2012). Done well, collaborative governance can support knowledge generation, social learning, and improved adaptivity (Berkes, 2009; Bodin, 2017). Many collaborative governance studies adopt theory and methods from social network analysis to examine how the structure of collaborative relationships can best generate positive outcomes (Bodin and Crona, 2009; Bodin, 2017; Bodin et al., 2017; Berardo et al., 2020).

We draw on this tradition in this article, presenting evidence from a study in Southeast Tanzania's Kilwa District to make two key contributions. First, we find that with the help of supportive collaborative networks, FSC-certified community-based forest management can be as effective as state-led forest management, represented in this case by some of Tanzania's National Forest Reserves (NFRs), in reducing deforestation risks. The characteristics of collaborative governance networks centered on village governments - in network analysis terms, the village governments' egonetworks - not only help explain which villages elect to engage in community forestry in the first case but also the effectiveness with which those systems stem subsequent forest loss. The reduced risk of forest loss within state-led forest management areas, by contrast, is almost entirely unaffected by village egonetworkss.

Second, different egonetwork characteristics can support or impede positive conservation outcomes at the village scale, regardless of whether the village hosts state-led NFRs or community-based forest management areas. Specifically, the more each village government's organizational partners are connected to one another, and the more civil society organizations collaborate with each village government, the lower the village's deforestation risk. More private sector organizations connected to village governments, however, are associated with higher deforestation risks. This suggests that not all egonetwork structures support positive conservation outcomes and that paying attention to focal governance actors' egonetwork characteristics could help support effective certified community-based forest management. If a combination of certified community-based forest management and robust collaborative governance networks can achieve similar reductions in forest loss as state-led governance, these approaches may be more desirable conservation tools from the perspective of community participation, livelihoods outcomes, and, potentially, resource intensity.

2. Theory

2.1. Collaborative networks in the context of community-based forest management

Context shapes whether or not community-based forest management is likely to benefit - or even be relevant to - different groups and locations (Hajjar et al., 2021; Muttaqin et al., 2019; Wright et al., 2016; Tole, 2010). While proponents hope community-based forest management can benefit forest quality and quantity, and support sustainable livelihoods (Alejo et al., 2022; Burivalova et al., 2017; Hajjar et al., 2021; Miteva et al., 2019; Oldekop et al., 2019; Sze et al., 2022; Takahashi and Todo, 2012), most studies focus on environmental outcomes, especially changes in forest cover.

Existing literature documents numerous conditions that affect both state-led and community-based forest management's performance, but the two approaches are sensitive to different contextual factors. State-led forest management, for example, may stand up to high extraction pressures, but it requires supportive institutional contexts and adequate resources to enforce rules and best practices (Bonilla-Meijía and Higuera-Mendieta, 2019; Coad et al., 2019; Feng et al., 2021; Graham et al., 2021; Nolte et al., 2013; Powlen et al., 2021; Schleicher et al., 2019). Hajjar et al. (2021), analyzing 643 cases of community-based forest management in 51 countries, on the other hand, provide evidence that four factors are particularly important for community forestry's effectiveness as a conservation tool. First, local biophysical conditions affect the practice's economic viability, as well as the nature of anthropogenic pressures on the forest. Second, like state-led forest management, community-based forest management requires a supportive institutional context - particularly secure tenure rights and effective governance. Third, features of the community-based forestry management system itself, such as the exact rules in operation, will affect its performance. Finally, local user group characteristics, such as community size and migration patterns, affect opportunities for collective action and local anthropogenic pressures on forests.

While collaborative network characteristics do not fall neatly into Hajjar et al.'s (2021) four categories, several studies suggest they also may affect community-based forest management's success. Generally, the literature indicates that local collaborative networks can help build the trust and social capital that help communities engage in successful collective action (Humphries et al., 2020; Lauber et al., 2008; Lubell and Morrison, 2021), while translocal networks may help forest managers access resources, skills, and knowledge (Arts and de Koning, 2017; Baynes et al., 2015; Butler and Current, 2021; Charnley et al., 2022; Humphries et al., 2020).

FSC certification provides a good example of how collaborative governance networks can be a part of community-based forest management. First, the certification process itself can be understood as a formal context that connects communities both to external actors and management institutions (Henriksen et al. 2022). Second, effectively implementing community forest management, let alone achieving sustainability certification, requires skills and resources that may not accompany the formal right to manage forests (De Royer, Noordwijk and Rosthetko, 2018; Tole, 2010). Communities often rely on the assistance of external organizations, which can provide funds, knowledge, legitimacy, connections, and other resources, to establish certified production in the first place (Butler and Current, 2021; Charnley et al., 2022). As Arts and de Koning (2017) document using a qualitative comparative analysis, these connections must be strong and characterized by a spirit of trust to be effective. These observations lead us to our first two propositions:

Proposition 1. High quality networks will be associated with the selection of areas into community-based forest management.

Proposition 2. Village egonetwork characteristics will account for some of certified community-based forest management's contribution to reduced forest loss.

While recent studies have suggested that networks are likely to be an important consideration in collaborative governance's success (see for example, Bodin, 2017; Schoon et al., 2017; Berardo et al., 2020), to our knowledge no study has conducted a large-N statistical test of this hypothesis in the case of community-based forest management. Arts and de Koning (2017) is the closest example of which we are aware. Using qualitative comparative analysis, they present evidence that robust extra-local networks can boost community-based forest management's contributions to local livelihoods and forest conditions. While their findings are highly suggestive, their approach does not permit assessing the possible contributions of different governance network characteristics to conservation outcomes. Distinguishing these contributions requires further engagement with social network theory as it relates to collaborative governance.

2.2. *Bonding and bridging in collaborative natural resource governance networks*

During the past two decades, natural resource governance researchers have begun to draw on network theory to help explain how patterns of social relationships among actors participating in, or collaborating around, resource governance processes affect environmental outcomes. The key claim from this research tradition is that the network structure of social interactions underpinning collaborative governance helps shape its effectiveness (Bodin, 2017). Although scholars acknowledge that there is likely "no single blueprint for well-performing collaborative networks" (Bodin et al., 2017, 289), researchers frequently argue that a combination of bonding ties - mutual connections among organizations in cohesive subgroups (Newman and Dale, 2007) - and bridging ties - connections between different sectors or groups - are often associated with effective outcomes (Bodin and Crona, 2009; Lauber et al., 2008; Lubell and Morrison, 2021).

Bridging ties can support certified community-based forest management because they cross boundaries between sectors or communities of practice (Berkes, 2009). As noted previously in our discussion of FSC certification, multi-sectoral networks linking different organizations can facilitate resource and information sharing, improve learning and adaptive capabilities, and channel support to local actors involved in resource governance (Rudnick et al., 2019; Schnegg, 2018; Ramirez-Sanchez and Pinkerton, 2009; Newman and Dale, 2007; Crona and Bodin, 2006; Hahn et al., 2006; Folke et al., 2005; Pretty and Smith, 2004; Pretty and Ward, 2001). Bridging ties might, for example, connect governmental and civil society sectors, or perhaps natural, social, and traditional knowledge communities (Bodin and Crona, 2009; Cash et al., 2006; Crona and Parker, 2011, 2012).

Considering bridging ties *en bloc*, however, risks assuming that all multi-sectoral collaborations have similar effects. More research is needed that distinguishes different types of multi-sectoral connections and links them to governance outcomes (Bodin, 2017). The co-presence of organizations with conflicting resource management interests can as easily produce dilemmas and tensions as synergies (Lubell and Morrison, 2021). Because pressures for timber extraction are linked to global value chains, for example, collaborations between village governments and the private sector might as easily indicate buyers' interest in building local alliances to better access resources as innovative collaboration (Jayathilake et al., 2021). Bridging ties between local communities and non-governmental conservation or development organizations (NGOs) that explicitly work to promote forest protection, on the other hand, are likely to introduce countervailing interests and norms that could push governance outcomes in a more conservation-friendly direction (Pacheco-Vega and Murdie, 2021). These ideas lead to our third proposition:

Proposition 3. Bridging ties with civil society organizations will be associated with reduced deforestation.

Because of the ambiguity of private sector organizations' role in the collaborative networks we study, we have no specific prior expectations about whether their association with forest loss rates will be positive or negative.

Like bridging ties, there are good reasons to think bonding ties might support effective community-based forest management. Bonding ties can enhance trust and reciprocity, facilitate collective action, support effective coordination (Coleman, 1988; Burt, 1995), and help build consensus (Ernstson et al., 2008; Crona and Bodin, 2006; Schneider et al., 2003). They can also facilitate tacit knowledge transfer (Crona and Bodin, 2006), monitoring of and compliance with common norms (Scholz and Wang, 2006; Dietz et al., 2003), and conflict resolution (Hahn et al., 2006). Bonding ties, therefore, may help compensate for institutional interests that work counter to sustainable use norms. This leads to our final proposition:

Proposition 4. Bonding ties will be associated with reduced rates of deforestation

While there are good theoretical reasons to expect characteristics of collaborative governance networks to be related to community-based forest management's effectiveness, few studies analyze the association between formal measures of bonding and bridging and conservation outcomes. As a result, while the performance of certified community-based forest management is expected to rely on the qualities of collaborative governance networks, we lack quantitative empirical evidence on these propositions.

3. Materials and methods

3.1. *Empirical setting*

Tanzania has experimented with decentralized natural resource governance for about two decades, attracting widespread attention. The country's forests were once communally managed under customary tenure (Kalumanga et al., 2018; Barrow et al., 2022; Kajembe, Nduwamungu and Luoga 2005), a practice shattered when first Germany and then Britain colonized the area, expropriating vast tracts for timber extraction and plantation forestry (Kostiainen 2012). Colonial conservation generally meant evicting indigenous groups from forests, after which wooded areas were subsumed under centralized management. Decades of independence notwithstanding, many aspects of the colonial settlement persist under the present NFRs (Kalumanga et al., 2018). Since the Participatory Forest Act of 2002, however, Tanzanian villages have been permitted to establish and manage their own community-based Village Land Forest Reserves (VLFRs). Ten years later, 400 reserves had been established (URT 2012), and their numbers have grown since.

We study eight village areas (3,796 km2) in Kilwa District, Lindi Region, in southeast Tanzania. Villages in Kilwa began experimenting with community-based forest management in the 1990s (Treue et al., 2014), and our study covers the period from 2000 to 2018, during which many villages in the district established VLFRs (see Fig. 1). Kilwa District has also hosted NFRs for many decades, providing a reasonable benchmark against which to compare VLFRs. Furthermore, because all the VLFRs we study obtained FSC certification, there should not be substantial variation in enforcement strictness across the villages, helping control for a critical factor noted in the literature (Nolte et al., 2013).

Starting in the 2000s, a local NGO called the Mpingo Conservation

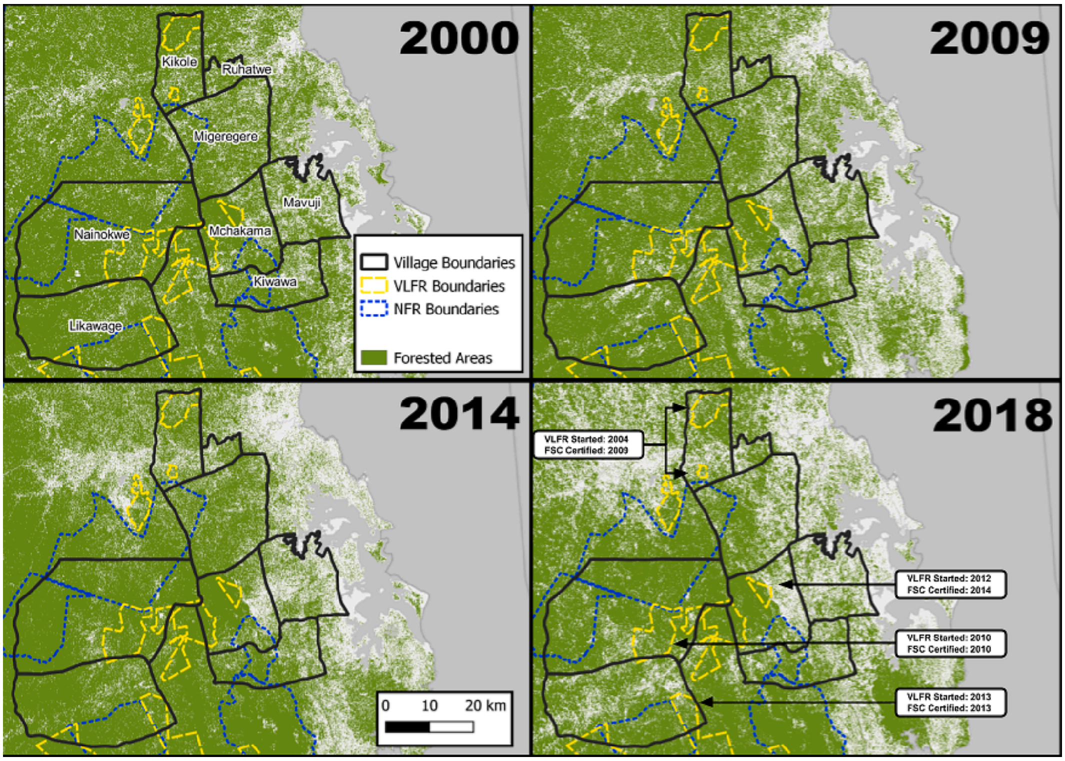

Fig. 1. Overview of forested areas in study villages and location of forest governance models in the Kilwa district. Yellow boundaries are Village Land Forest Reserves (VLFRs) and blue boundaries are National Forest Reserves (NFR). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Program, now the Mpingo Conservation and Development Initiative (MCDI), started promoting VLFRs in Kilwa. Helping broker ties with organizations in multiple sectors to help interested villages connect to markets and relevant expertise, their work was critical for achieving FSC certification (Mwamfupe et al., 2019, 2022). With a notable exception of one VLFR earning an average of $65,000 annually, incomes from the reserves are generally modest - less than $10,000 per year (Charnley et al., 2022a).

3.2. Data collection

Like much of the existing impact assessments of community-based forest management, we focus our analysis on changes in forest cover. While this is by no means the only possible indicator of conservation effectiveness, maintaining forest cover is nonetheless a key objective for global biodiversity efforts and one of many desirable outcomes of community-based forest management. To test the propositions about selection, bonding, and bridging outlined in the previous sections, we combine satellite-based data on forest change with village egonetwork data created through a combination of archival sources and key informant interviews during fieldwork in the study villages. We provide further details on these data collection methods before discussing how we analyze the resulting datasets.

3.2.1. Fieldwork

We conducted extensive fieldwork in the Kilwa region over several visits from 2016 to 2019. Based on early exploratory fieldwork and desk research, the project team selected eight study villages in the area, covering villages with only open access lands (N=2), villages hosting NFRs (N=6), and villages with VLFRs (N=4). To be clear, all villages hosting VLFRs also hosted at least a small section of a NFR, and all villages had considerable stretches of open access lands. This combination of governance regimes made the study area ideal for using state-led forest management as a benchmark against which to compare community-based forest management. Two field researchers had multiple extended stays in the villages from 2016 to 2019, conducting key informant and focus group interviews, collecting archival material, and gathering ground-truthing data for land-cover classification. A larger research team did shorter field visits, conducted key informant and focus group interviews with village governments and collaborating organizations, helped develop the data collection protocol, and coded qualitative data (for details see Ponte et al. 2022).

Key informant interview sampling was conducted during village visits, in consultation with the study villages' natural resource committees and village councils, triangulating with archival materials to ensure that key sections of the village communities were represented. In all cases the team interviewed leaders of relevant village government committees and village councils, as well as elders who had retired from their government responsibilities. The exact number of interviewees in each village depended on the availability and willingness of members of these groups to participate. In this article, we mainly draw on the interviews with villagers who at some point were involved in government activities related to forestry (Mwamfupe et al., 2019, 2022).

3.2.2. Village egonetwork data collection

Examining focal governance actors' egonetwork characteristics is a common approach for studies investigating networks' effects on environmental management (Barnes et al., 2017; Bodin et al., 2017). Village governments' egonetworks consist of the village government, the partner organizations to which it is connected, and the connections between the partner organizations. The research team attempted to identify the evolving ties within these egonetworks as a whole for all villages from 2000 to 2018. We coded the village egonetworks longitudinally into time periods of 5-years - 2000–2004, 2005–2009, 2010–2014 and 2015–2018 - covering the entire period from before the first village entered a VLFR to the last full year of data collection.

The field researchers applied a combination of event- and document-based sampling strategies with respondent-driven link tracing

(Heckathorn and Cameron, 2017) to identify interorganizational collaborations, such as project partnerships with civil society organizations and community forest enterprises. To accomplish this, the research team triangulated information from several sources. First, all visitors to the study villages are obliged to sign village guestbooks, which provide records of key organizational stakeholders that had been active in the village across time. To address missing data due to lost guestbooks, recording lapses, or similar problems, the research team also consulted policy and conservation project documents obtained from national archives, transcripts of key informant interviews, and stakeholder organizations' websites. After using these materials to generate time-stamped collaborative relationship data, the team re-interviewed village council and natural resource committee members, as well as representatives of villages' external collaboration partners, about their organizations' collaboration on sustainable forest management, documenting relationships from both sides of the dyad. During these interviews, the team asked respondents to fill in ties not yet on the list and to provide further information on collaboration timing. After collecting the village egonetworks, we coded actors into organizational types. Civil society organizations and private sector organiations are of particular interest in the literature on cross-sectoral network ties. We coded nonprofit organizations promoting the interests of citizen groups independently of governments as civil society organizations, while corporations operating for profit in the marketplace were coded as private sector organizations. We present a list of the types of cross-sectoral organizations included in the analysis in Table A5.

Given the time- and resource-intensity of fieldwork required to track the evolution of collaborative governance networks in the study region, it was only feasible to collect these data for a small number of villages over time. This unfortunately limits the total variance in village egonetwork characteristics that could be observed, with the result that it was necessary to constrain our modeling choices to relatively simple measures. For example, while we collected data on the types of ties between organizations in the villages' egonetworks, we lack sufficient observations to distinguish the contributions of different types of ties.

3.2.3. *Land-cover data collection*

We generated our forest-cover dataset using supervised random forest classification, trained with Google Earth Engine (https://code.earthengine.google.com/). We used seven classes adopted from the system presented in the Food and Agriculture Organization of the United Nations (FAO 2022), categorizing land cover as barren, cropland, human settlement, grassland, woodland, coastal forest, or water (see section on Overview of Land-Cover Classes in Supplementary Materials). For the purposes of the analysis reported here, we combined the FAO's woodland and coastal forest into a single forest category, grouping all other categories together as non-forest.

We created separate training and testing datasets from ground-truthing points collected during the fieldwork, supplemented with georeferenced topo sheets and very high-resolution Google Earth imagery covering the study area (Klinkenberg, 2019). In total, we generated 4500 points, 2000 of which were forest cover. We randomly assigned 60% of our 4500 human-coded points for training and validation, reserving the remaining 40% as a test dataset and kept this division consistent for all algorithm runs.

Using these techniques, we constructed reliable forest-cover datasets for the study area in 2000, 2004, 2009, 2014, and 2018 at a 10-meter resolution from annual composite imagery from Sentinel-2, Sentinel-1, Landsat-8, Landsat-7 and Landsat-5, collected with Google Earth Engine. To improve classification accuracy, we applied standard radiometric and atmospheric error correction (Japan Association of Remote Sensing, 2022; Turks, 1990); computed the natural digital vegetation index, enhanced vegetation index, normalized difference water index, normalized difference built-up index, ratio (3:5–4:6), ratio (5:4–6:5), ratio (2:11), and Sentinel-1 values (Xue and Su, 2017); and added a digital elevation model (Farr et al., 2007) to the algorithm inputs.

To identify land-cover classes, we used a random forest classifier in Google Earth Engine (Pal, 2005). Following Gallego (2004), we assessed our predictive accuracy using a confusion matrix, which compares the agreement between pixel classifications and ground-truthed land cover. Using our validation sample, we found that overall accuracy for all classified images averaged 89.7%, with a Kappa coefficient above 0.94. We present the confusion matrices for each year in Tables A1 through A3.

3.3. *Measures and models*

After collecting the data, it was necessary to conduct a series of calculations to produce the independent and dependent variables used in our models. First, we computed a series of network measures focusing on each village's egonetwork. Second, we converted the classified satellite imagery described above into a longitudinal dataset suitable for modeling the changes in risk of deforestation for individual forest pixels over time. Third, we conducted propensity score matching to create a balanced dataset facilitating comparisons between state-led and community-based forest management areas. Finally, we estimated weighted Cox proportional hazards models using the propensity score weights and geographic fixed effects to assess the relationship between network characteristics, forest management type, and deforestation risks.

3.3.1. *Village egonetwork characteristics variables*

Using our village egonetwork data, we identified the number of stakeholder organizations in private and civil society sectors active on forest issues in each village at the time of our image collection, measuring the extent of cross-sectoral bridging in each village. To measure the extent of bonding ties, we measured the percentage of all situations in which two connected organizations both collaborate with a common third party, a statistic known as the percentage of closed triangles. We present the descriptive statistics of these variables in Figure A1 and Table A4.

3.3.2. *Forest loss variable*

Using the forest cover datasets described above, we randomly sampled 5 million pixels that were forested as of the first year of observation (2000), observing their status at each period until they either were deforested or the observation period ended. This created our dependent variable - a binary indicator tracking whether a pixel was deforested in a given time period.

3.3.3. *Matching*

A key challenge in estimating the impacts of different forest management models is that forest protection often exhibits strong selection biases, as it can be attractive to locate protection in areas that are not in fact at high risk of deforestation (Andam et al., 2008; Pfaff et al., 2013). Furthermore, there may be different incentives and political pressures affecting the location of different forest management types (Pfaff et al., 2015), making it difficult not only to compare different approaches against unprotected areas, but also against each other. While we observe VLFR areas before and after they begin operation, the study area's NFRs far predate our observation period, which makes it difficult to use them as a benchmark. Furthermore, because our first proposition relates to village governments' egonetwork characteristics and selection into community-based forest management, it was desireable to investigate selection processes directly.

To accomplish these goals, we conducted propensity-score matching at the level of individual pixels. A common strategy for impact assessments (Andam et al., 2008; Jayathilake et al., 2021; Heilmayr and Lambin, 2016), propensity score matching refers to a range of strategies for generating quasi-experiments from observational data by constructing datasets of observations that would be plausible if the treatment conditions were randomized.

While most applications in forest impact analysis have focused on creating matching samples from a single treatment group with a control group, because we use NFRs as a benchmark comparison for VLFRs, we had two treatment groups. For this reason, we conducted our matching using algorithms available in the Toolkit for Weighting and Analysis of Nonequivalent Groups (TWANG; Griffin et al., 2014). TWANG takes a machine-learning approach to matching, using generalized boosted models to weight observations to achieve balance on confounding variables. The approach builds on the observation that a propensity score - a vector of values measuring the probability that a given observation is assigned to a particular treatment condition - is in principle sufficient to adjust comparisons between groups to mitigate biases resulting from observed confounding variables (Rosenbaum and Rubin, 1983). Often this is done using predicted probabilities that an observation is in one group or another computed from logistic or multinomial logistic regression models. Because propensity score matching's goal is to incorporate as much information from the potential confounding variables as possible into the propensity score in order to reduce estimation biases, it can be beneficial to estimate multiple models with different variable transformations and interactions to maximize model fit and, thereby, incorporate more information into the propensity score. The space of possible models, however, is vast, and researchers are unlikely to feasibly test more than a few possible permutations. Furthermore, using logistic regression requires making parametric assumptions that may not be appropriate for a given application. Generalized boosted models, by contrast, work by generating a series of regression trees whose outputs are combined to estimate propensity scores. This machine-learning approach provides a way to efficiently and non-parametrically estimate the propensity score (McCaffrey et al., 2004). We present our matching variables in Tables 1 and 2 below and visualize our post-matching comparisons in Figure A2 in the online appendix.

3.3.4. Modeling

Following the literatures on collaborative governance and networks, we hypothesize that village governments' egonetwork characteristics will shape community-based forest management's impacts on forest loss. We anticipate that these impacts will be visible in three ways. First, network characteristics will affect the selection of particular areas into collaborative governance regimes in the first place (Proposition 1). Second, village governments' egonetwork characteristics will account for a portion of VLFRs' estimated impacts on forest loss (Proposition 2). Third, bridging ties to civil society (Proposition 3) and bonding ties (Proposition 4) within village governments' egonetworks will be associated with reduced forest loss.

To test these propositions, we trace forest loss at a 10-meter by 10-meter resolution before and after the introduction of VLFRs while following the parallel evolution of village egonetworks, allowing us to disentangle how much avoided forest loss can be attributed to governance and how much can be attributed to village egonetwork characteristics. Because some boundaries in the region are contested, there are a few locations where the claimed boundaries of the NFRs and VLFRs overlap. To avoid biased measurements arising from these disputed regions, we exclude these contested areas from our analysis.

Table 1
Distribution of variables used for propensity score matching.

Variable	Minimum	Median	Mean	Maximum
Distance from Croplands (M), 2000	0	120	190	1,960
Distance from Human Settlement (M), 2000	0	1,140	1,450	6,340
Distance from Forest Edge (M), 2000	0	63	100	1,220
Distance from Main Trunk Road (M), 2000	0	7,250	7,600	19,410
Coastal Forest	0	0	0.192	1
Woodland	0	1	0.808	1

Table 2
Distribution and post-matching weighted effective distribution of forest management type observations.

Management Type	Number of Observations	Effective Number of Observations after Matching Weights Assigned
Open Access	3,625,793	667,804.7
National Forest Reserve	1,284,323	1,028,112
Village Land Forest Reserve	89,884	33,994

We combine remotely sensed land-cover and other geographic data for the four time periods with ego network data identifying study village egonetwork characteristics. Using Cox (1972) proportional hazards regression models, we estimate the association between 10-meter by 10-meter forested areas' risk of deforestation during a given observation period, our dependent variable, and our independent variables of interest: measures of village egonetwork characteristics and a categorical indicator variable of the forest management type in place. We also control for residual unmeasured and unmatched geographic factors that may contribute to deforestation by including a binary variable dividing the study area into 10-kilometer by 10-kilometer grid cells (less one, in total 51) and a continuous measure of the natural logarithm of distance to the nearest trunk road. Finally, we test for possible spillovers from VLFRs by including a binary variable that is a 1 if a pixel is within 1 km of an active VLFR and is 0 otherwise.

To assess our claims about egonetworks and selection effects, we compare the estimated coefficients for pixels under active VLFRs when ignoring and when controlling for village egonetwork characteristics under four different model specifications: with and without matched samples and with and without geographic fixed effects. Because both pixel-level matching of the governance types and geographic fixed effects are designed to mitigate selection effects, we expect that the difference between the estimated coefficients for active VLFR areas when ignoring and when controlling for village egonetwork characteristics will be smaller after adjusting for selection effects.

Similarly, testing our proposition that village egonetworks will account for some of VLFRs' estimated effectiveness requires comparing the coefficients for active VLFRs in models that do and do not control for village egonetwork characteristics. We would expect to see reductions in VLFRs' estimated forest loss impacts when controlling for village egonetwork characteristics.

Our test of the impacts of bonding and bridging in village governments' egonetworks is rather more conventional than those for the previous two hypotheses. Here, we simply anticipate that higher values of our bonding and bridging measures will be associated with reduced deforestation in the village in question.

4. Results

Across the period observed, we documented substantial variation in village egonetwork characteristics (see Fig. A1, Appendices). As noted above, several villages that partnered with the Mpingo Conservation and Development Initiative (MCDI) developed significantly larger networks, with higher levels of cross-sectoral collaboration than was the case for the other villages. To be clear, the construction of robust collaborative networks, as several interviewees noted, was part of MCDI's strategy to help villages form VLFRs, achieve FSC certification, and broker contracts with buyers seeking certified timber products. Put another way, robust village egonetwork structures were an intended correlate of certified sustainable community-based forest management in the study villages, not an accessory.[2]

This point speaks to our expectations that village governments' egonetwork characteristics should affect the selection of particular areas into VLFRs (Proposition 1). If this were the case, we would expect to see that when adjusting for network characteristics, the estimated association between VLFRs and forest loss would change less substantially in models that adjust for selection effects than in models that do not. To assess this proposition, therefore, we can compare the coefficient estimates for VLFRs in models estimated with and without propensity-score matched samples and geographic fixed effects. Fig. 2 presents these comparisons. Comparing the estimated coefficients for VLFRs with and without adjusting for village egonetwork characteristics in models with unmatched samples and without geographic fixed effects (upper-left panel) to the difference in models adjusting for selection effects (bottom-right panel), it is clear that the difference is substantially reduced when adjusting for selection effects. These patterns are consistent with evidence from the fieldwork that MCDI specifically worked to build networks supporting villages to achieve FSC-certified community-based forest management.

Fig. 2 also allows us to assess the evidence for the claim that village governments' egonetwork characteristics partially explain VLFRs' effectiveness in reducing deforestation (Proposition 2). First, there is evidence that VLFRs do perform well in lowering the odds of forest loss. In models without geographic fixed effects (Fig. 2 upper panels), NFRs would appear to substantially outperform VLFRs in how effective they are at reducing the odds of forest loss. In the model with no fixed effects, no matched samples and no network covariates (Fig. 2 upper left panel), the average odds of a pixel being deforested are about 60 percent lower in NFRs than open access lands, while the odds are only 35 percent lower in VLFRs than open access areas. In the model with no fixed effects and no village egonetworks but with matched samples (Fig. 2 upper right panel), the odds of deforestation are estimated to be 45 percent lower in NFRs and just 25 percent lower in VLFRs, suggesting that selectivity of areas into particular types of governance accounts for a substantial portion of the odds reduction in both cases. The buffer zone area behaves similarly to the VLFRs, but just with a somewhat lower odds reduction, suggesting these areas are not causing negative spillovers.

The models with geographic fixed effects paint a very different picture of the relative effectiveness of NFRs and VLFRs. Adjusting for invariant geographic factors via the fixed effects but without matched samples (Fig. 2. bottom left panel), we estimate that VLFRs and NFRs are roughly equally effective at reducing deforestation odds. In fact, in these models VLFRs are doing slightly better at reducing risk (with about five percentage points lower odds of deforestation relative to open access areas). But in the models with geographic fixed effects and matched samples (Fig. 2 bottom right panel) but no village egonetworks this difference is entirely equalized, suggesting that net of selectivity NFRs and VLFRs perform equally well in reducing forest loss.

Importantly, a substantial part of VLFRs' effectiveness, even after adjusting for selectivity using both matched samples and geographic fixed effects, can be accounted for by the village egonetworks that evolve alongside them. In the matched sample with geographic fixed effects, the model not accounting for village egonetwork characteristics estimates that NFRs reduce the odds of forest loss by 24 percent and VLFRs reduce the odds by 23 percent, a difference that is not statistically significant. By comparison, the model accounting for village egonetwork characteristics still estimates that NFRs reduce the odds of forest loss by 24 percent, but that VLFRs net of networks only reduce the odds of forest loss by 20 percent, now significantly less than NFRs. By implication, after adjusting for selectivity via geographic fixed effects and matched samples, village egonetwork characteristics account for none of the risk reduction in NFRs, while they account for 17 percent of VLFRs' risk reduction. Together these findings imply that VLFRs with network characteristics conducive to positive conservation outcomes can stem deforestation at least as effectively as NFRs.

Still further, village egonetwork characteristics are associated with substantial differences in the risk of forest loss, regardless of the type of forest management in question. In all of our models, the estimated network coefficients remain statistically and substantively significant even when adjusting for the presence of different governance regimes. These results indicate that, while village egonetworks are a critical component of the effectiveness of VLFRs in the study region, network characteristics can also contribute to forest protection across the entire village landscape.

What village egonetwork characteristics stem deforestation? In Fig. 3 we illustrate the coefficient estimates for our egonetwork variables from the same models reported in Fig. 2, also including coefficient estimates for models that do not adjust for the presence of NFRs and VLFRs for comparison purposes. As was the case in Fig. 2, Fig. 3 demonstrates that accounting for selectivity makes a substantial difference in interpreting the associations between some, but not all, of the measured village egonetwork characteristics and deforestation reduction. While the estimated coefficient for Civil Society Degree, our first measure of bridging, does not change substantially between the unmatched and matched models, its magnitude is substantially reduced when considering geographic fixed effects, though in all cases its estimated coefficient, as expected, is negative (Proposition 3). In the matched model with geographic fixed effects, which provides our best estimate of the Civil Society Degree's association with deforestation, the median village would be associated with about a 3 percent reduction in deforestation odds, while villages with 6 connections - the upper quartile observed - would be expected to have 6 percent lower deforestation odds than a village with no such connections. The highest number of organizations observed, 12, would therefore be associated with about a 12 percent reduction in deforestation odds, a bit over half the estimated association between VLFRs themselves and reduced deforestation.

Perhaps the most interesting result in Fig. 3 relates to our second bridging measure, Private Sector Degree. While, like Civil Society Degree, Private Sector Degree is associated with a reduction in deforestation odds (though to a lesser extent), when adjusting for geographic fixed effects, the measure is associated with a substantial increase in deforestation odds. At the median village egonetwork value of 2 private sector actors, we would already expect deforestation odds about 12 percent higher than for a village with no private sector actors, and at the upper quartile value of 4 private sector actors, we would expect as much as a 24 percent difference. This difference in estimated coefficients suggests that private sector actors may be attracted to areas that have relatively lower deforestation rates, but net of other network characteristics and selectivity their engagement in such places is, in turn, associated with increased deforestation risk.

Finally, the estimated association between the Percentage of Closed Triangles, our indicator of bonding ties, and deforestation is negative and quite stable across models, though modest (Proposition Four). In the model with both matched samples and geographic fixed effects, for

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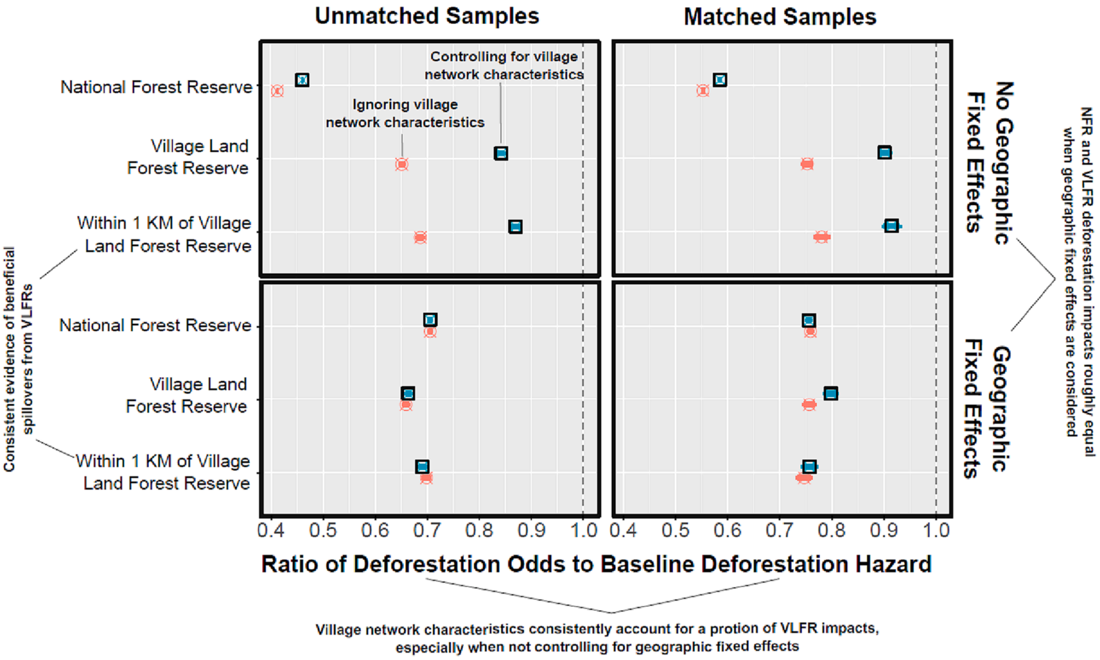
[2] The World Wildlife Foundation (WWF), MCDI's primary funder during the period, saw MCDI as an organization with sufficient local legitimacy and social capital to facilitate community-based forest management under FSC certification. MCDI started reaching out to communities in the early 2000s and was instrumental in helping to select and map villages deemed capable of going through land titling and FSC certification process. This was part of MCDI and WWF's broader regional strategy to channel power and resources to local communities while promoting sustainability norms in areas with exceptional ecological value, a factor which also figured in selecting villages. MCDI funded and assisted villages with the transition to community ownership and certification but also helped village governments find project partners such as timber firms, certification agents and other NGOs (Mwamfupe et al., 2019, 2022). Evidence from our fieldwork and interviews (plus cross-village survey data) show that all villages who entered the VLFR regime displayed high awareness of forest conservation issues compared to villages who did not enter, and interviewees often linked this difference to their partnership with the MCDI and other NGOs (Mwamfupe et al., 2019).



Controlling for village network characteristics

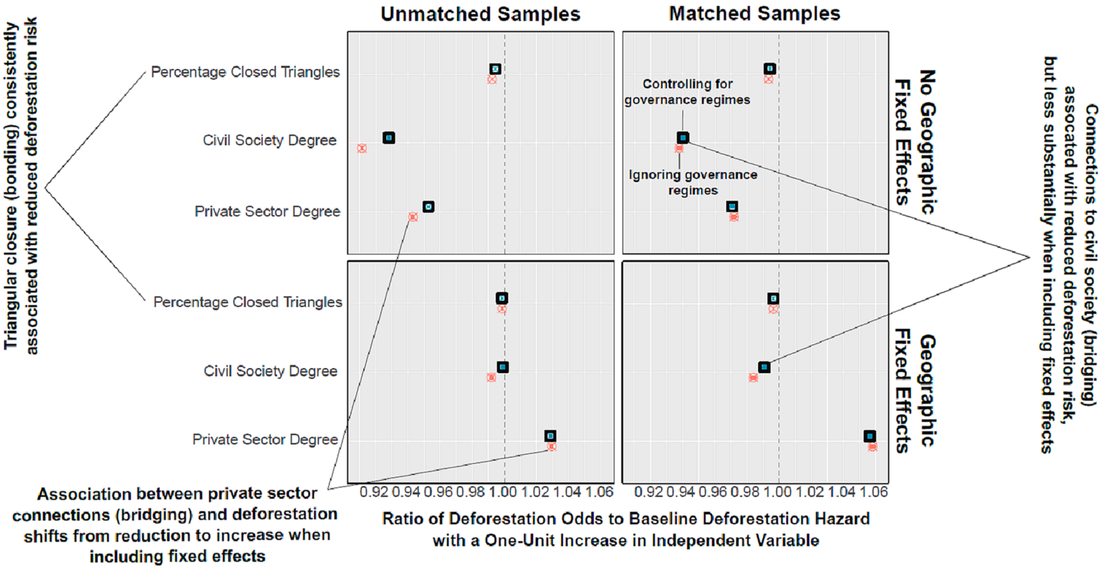
Ignoring village network characteristics

Consistent evidence of beneficial spillovers from VLFRs

NFR and VLFR deforestation impacts roughly equal when geographic fixed effects are considered

Village network characteristics consistently account for a protion of VLFR impacts, especially when not controlling for geographic fixed effects

Fig. 2. Estimates of Cox proportional hazard models for governance types in models with and without network covariates and matched samples. Coefficients are presented on the odds scale. Wide lines represent 95 percent confidence intervals. Narrow lines represent 99 percent confidence intervals. Odds ratio coefficients are multiplicative, so a one-unit increase in the independent variable is associated with a change in the odds of deforestation of a pixel in a period of the coefficient value times the existing odds. All estimates of National Forest Reserves (NFRs) and Village Land Forest Reserves (VLFRs) are relative to open access forest areas.



Controlling for governance regimes

Ignoring governance regimes

Triangular closure (bonding) consistently associated with reduced deforestation risk

Connections to civil society (bridging) assocated with reduced deforestation risk, but less substantially when including fixed effects

Association between private sector connections (bridging) and deforestation shifts from reduction to increase when including fixed effects

Fig. 3. Estimates of the effect of village egonetwork characteristics on the effectiveness of villages at reducing the risk of deforestation (log-odds) in the complete model with matched samples adjusting for the governance covariate. Wide lines represent 95 percent confidence intervals. Narrow lines represent 99 percent confidence intervals.

example, a move from 0 percent to the population median of 8.6 percent closed triangles would be associated with about a 1.5 percent reduction in expected deforestation odds. That said, for the few cases of 100 percent triangular closure, the estimated reduction in deforestation odds would be approximately 20%, comparable to the estimated impact of VLFRs in the same model.

5. Discussion

Our overall evidence indicates that community-based forest management can be as effective as state-led forest management in reducing deforestation in Tanzania's Kilwa district. Only in the case of community-based forest management, however, do village egonetwork characteristics account for a substantial portion of effectiveness. Furthermore, village egonetwork characteristics appear to shape the selection of certain areas into VLFRs in the first place. Our evidence also indicate that some, but not all, network characteristics contribute to VLFR effectiveness. To be clear, we should interpret these results as an indicator of these mechanisms' capacity to restrain deforestation relative to a counterfactual situation in which they were not active, rather than to say that these mechanisms are reducing deforestation in an absolute sense. With infrastructural development and growing commercialization of sesame crops, in particular, forest loss in Kilwa District climbed throughout the 2010s, anti-deforestation efforts notwithstanding, though some of this loss was offset by simultaneous regeneration of fallowed swidden areas (Gallemore et al., 2022).

As documented in the existing literature, both state-led and community-based forest management rely on contextual factors to be successful. For community-based management in particular, local support and moderate-to-low commercial pressures are important (Bonilla-Meijía and Higuera-Mendieta, 2019; Nolte et al., 2013). Our findings suggest village egonetwork characteristics should be taken seriously as another factor potentially influencing certified community-based forestry's success. When village's egonetworks are conducive to conservation, certified community-based forest management can net of selectivity perform at least as well as state-managed protected areas.

Our results are consistent with theoretical expectations from several previous studies. First, the findings regarding connections to civil society and private sector actors indicate that bridging ties can also have important impacts on forest conservation. However, the opposite effect of ties to civil society versus private sector organizations suggests that the character of external organizations' engaged in collaborative networks around forest management can be critical. Consistent with previous studies that have found that when NGOs link up effectively with local communities, they can have positive effects on environmental outcomes (Pacheco-Vega and Murdie, 2021) and potentially restrain excessive extraction (Vélez et al., 2020), we find that partnerships with civil society organizations can mitigate deforestation risks. Conversely, private sector connections are associated with increased forest loss, consistent with work finding that market development can incentivize forest extraction (Jayathilake et al., 2021). Further, these findings are consistent with calls to pay closer attention to actors' characteristics in the analysis of polycentric governance systems (Lubell and Morrison, 2021).

Second, the finding that bonding ties can modestly support conservation effectiveness is also consistent with expectations, though, as noted above, the effect is modest at the levels of triangular closure observed in our data. As noted previously, the literature lists numerous possible mechanisms by which bonding ties could improve collaborative natural resource governance outcomes. A few examples include building trust, establishing consensus, supporting social learning (Folke et al., 2005; Pretty and Smith, 2004), providing opportunities for monitoring, and facilitating norm enforcement (Lubell et al., 2012). Any or all of these could be factors in this case. Our data unfortunately do not permit us to make any claims about which mechanisms drive the patterns we observe, but this could be a promising area for future research.

Finally, MCDI's role as a catalyst for village egonetwork formation was a critical factor in the developments analyzed in this study. While in some ways this role makes it difficult to generalize from our study villages, MCDI is not fully unique. Local NGOs have been found to be important in building organizational environments promoting effective community-based initiatives on other continents, as well (Friedman et al., 2020). Indeed, as Lubell and Morrison (2021) argue, effective balances of bonding and bridging ties can be an important means of building adaptive capacity in environmental management. Indeed, an important question for future research might involve the degree to which a local network builder like MCDI is necessary for effective engagement in certified community-based forest management.

While the situation in Kilwa District is instructive, therefore, it is only an initial foray into quantitative studies of collaborative governance networks' contribution to natural resource management outcomes. Future research also should seek to adjudicate how different network mechanisms, such as power imbalances, resource sharing, or the diffusion of tacit knowledge, might shape conservation outcomes, issues that could not be addressed with the data reported on here. As noted in the methods discussion, the time- and resource-intensity of longitudinal network data collection limited our analysis to eight villages in a single district of Tanzania. This limited the extent and detail of network hypotheses that we could test, as well as the generalizability of our findings to other cases. While our results indicate that studies of collaborative forest management would do well to explicitly consider collaborative governance networks' characteristics, network variables' effects could differ substantially for different resources or in different locations (Gallemore et al., 2022; Henriksen et al., 2022b). Continuing this direction of inquiry will require well-resourced and creative approaches to collect longitudinal network data for a substantially larger number of well-selected observations.

6. Conclusion

In this paper we assessed the relative effectiveness of state-led and community-based forest management in Kilwa, Southeast Tanzania, comparing the evolution of village egonetworks and deforestation risk from 2000 to 2018 in open access, NFR (state-led) and VLFR (certified, community-based) areas. Accounting for selectivity but not networks, our analyses reveal that NFRs and VLFRs are virtually indistinguishable in their effectiveness at stemming forest loss. Accounting for selectivity and variation in village governments' egonetworks, however, shows that risk reduction in VLFRs is partially reliant on conducive collaborative governance network characteristics, which is not the case for NFRs. Village's organizational egonetworks, in other words, enable effective forest conservation in VLFRs. Moreover, village egonetworks have an independent impact on the risk of forest loss regardless of whether or not formal management approaches, whether state-led or not, are present. We find that, regardless of management approach, village egonetworks with many bridging ties civil society organizations and many bonding ties among actors in the collaborative network have lower deforestation risks, whereas village egonetworks with more private sector organizations have a heightened risk of deforestation. Our results suggest that FSC-certified community-based forest management in Kilwa District performs as effectively as state-led governance in slowing deforestation and relies on village egonetworks to do so. Our paper highlights the potential benefits of deliberate investment in local networks for promoting effective community-based forest management.

CRediT authorship contribution statement

Henriksen contributed to all parts of the research and wrote the article alongside Gallemore, who also helped with conceptualization, conducting formal analysis, developing code/software and visualizing results. Kamnde helped curate and analyze satellite data and created the classified land-cover raster data used to identify forest loss. Silvano took primary responsibility for collecting village network data. **Silvano**, Mwamfupe and Olwig coordinated and designed fieldwork activities. All authors contributed comments and text to the manuscripts.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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