Innovation diffusion within large environmental NGOs through informal network agents

Yuta J. Masuda[1*], Yuqing Liu[2], Sheila M.W. Reddy[1,3], Kenneth A. Frank[2], Kyle Burford[4], Jonathan R.B. Fisher[5], Jensen Montambault[1,6]

[1] Global Science, The Nature Conservancy, 4245 Fairfax Dr #100, Arlington, VA 22203
[2] Department of Counseling, Educational Psychology and Special Education, Michigan State University, East Lansing, MI 48824
[3] Chief Strategy Office, The Nature Conservancy, 4245 Fairfax Dr #100, Arlington, VA 22203
[4] Conservation Systems and Services, The Nature Conservancy, 4245 Fairfax Dr #100, Arlington, VA 22203
[5] Center for Sustainability Science, The Nature Conservancy, 4245 Fairfax Dr #100, Arlington, VA 22203
[6] Science for Nature and People Partnership, National Center for Ecological Analysis & Synthesis, 735 State Street, Suite 300, Santa Barbara, CA 93101

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The Sustainable Development Goals present opportunities for environmental non-governmental organisations (ENGOs) to address new challenges. Such innovation requires dynamism and adaptability that large ENGOs may lack, and flatter organisational structures common to large ENGOs may limit the efficacy of top-down diffusion of innovative ideas or approaches. Instead, diffusion may occur through informal networks. We conducted a network experiment to estimate the role of informal boundary spanners (IBSs) – individuals who cross internal organisational boundaries (e.g., departmental or geographic) via their informal social networks – for diffusing innovations in a large ENGO. We find they are four times more likely to diffuse innovations than non-boundary spanners, although organisational positions (e.g., formal organisational hierarchy) can moderate this behaviour. We also find evidence they play a role in changing attitudes in favour of the innovation. These findings highlight how IBSs can drive organisation-wide diffusion of innovations in ENGOs to strengthen capacity to address pressing sustainability challenges.

Recent sustainability initiatives, such as the Sustainable Development Goals[1], have provided an opportunity for environmental non-governmental organisations (ENGOs) to address human well-being and environmental goals[2]. But to do so, ENGOs must rapidly diffuse innovative inter- and multidisciplinary approaches that go beyond traditional approaches to conservation[3–6] and catalyse organisational learning, adoption, and adaptation[3,4,7,8]. This is especially critical for large, decentralized organisations that may lack sufficient direct authority or staff oversight to guarantee uptake of new resources and approaches. For instance, large conservation organisations, such as the World Wildlife Fund and The Nature Conservancy, operate in dozens of countries in diverse contexts, making top-down change challenging. Organisational leaders may appeal to formal authority[9] to diffuse innovations and promote organisational learning, but these approaches assume innovations can spread and be integrated through rigid, formal, and hierarchical organisational structures. Further, these approaches can be costly and ineffective[9,10].

An alternative approach is to leverage informal networks that closely represent actual communication channels and relationships. Informal networks may provide a more effective and holistic way of spreading and promoting innovations for organisational learning. Social network theories have long hypothesized key actors within informal networks play a significant role in diffusion and learning[11–15]. Within this large literature, IBSs in particular are uniquely positioned within informal social networks to diffuse innovations and promote organisational learning, especially in the early stages of intraorganisational diffusion of innovations[16–20]. IBSs are self-selected individuals that are strongly tied to staff within and outside their day-to-day (i.e., informal) work environments (i.e., clusters), and are distinct from formal boundary spanners who hold formal organisation roles that include boundary spanning activities[20,21,29]. Research has found IBSs can facilitate the flow of information between people or groups that may have minimal communication with each other[17,20–23]; are uniquely situated to develop insights into organisational structures and cultures[21]; often straddle multiple organisational units and may demonstrate unique skills to handle complicated tasks in different contexts[20,21,24,25]; and are more receptive to new knowledge and more responsive to change[26]. IBSs differ from bridges (i.e., actors tying two loosely connected clusters) and other actors within informal networks[22], as they balance the advantages of bridging (i.e., exchanging information between groups) and bonding (i.e., consolidating the collaboration within their primary group) by distributing their social capital equally to projects within and outside their cluster[27]. They also provide less redundant information[11], and are more efficient in spreading information inside and outside their cluster[28] compared to staff with similar degree centrality or transitivity. IBSs may possess the freedom and motivation to cross the divisional, hierarchical, and geographic boundaries, which are barriers formal managers and boundary spanners must contend with[30]. While IBSs, bridges, and formal boundary spanners may share similar network statistics, such as betweenness centrality, IBSs may fundamentally differ from other network actors because they are identified by taking into account the cohesiveness of network structures, which differs from bridges (i.e., those spanning between two clusters) or formal boundary spanners (i.e., those identified relative to formal boundaries, such as departments). The network position of IBSs uniquely situates them to diffuse innovations.

Despite their potentially significant role in diffusing innovations for organisational learning, no study has experimentally tested whether IBSs diffuse more information about an innovation than non-boundary spanners. Studies examining boundary spanners are often limited to smaller social networks[31,32], or only investigate formal boundary spanners (i.e., actors whose primary responsibilities include boundary spanning activities)[20,28,33]. Studies on large organisations tend to rely on social network surveys to gather data, but this approach can suffer from non-trivial non-response and lead to gaps in social network structures[34]. Further, it is extremely difficult, if not impossible, to employ an experimental design with large gaps in social network structures[26]. Studies testing aspects of diffusions of innovations using social network experiments have been in non-organisational social networks, such as Facebook[35], or have randomized participants into artificial networks[12]. We address these gaps by using rich administrative data covering over 800 individuals from The Nature Conservancy (TNC), one of the world's largest non-profit conservation organisation[36], to construct a bipartite network[37–39] and experimentally test IBSs' role in diffusion of innovations for organisational learning. Thus, our approach allows us to identify IBSs in a large ENGO, randomly assign them to experimental conditions, and estimate their role in diffusions of innovations for organisational learning.

We utilize Conservation by Design (CbD) 2.0's development and the rollout of an accompanying tutorial on human well-being and conservation (hereinafter tutorial) to experimentally test whether IBSs diffuse innovation for organisational learning compared to non-boundary spanners. CbD 2.0 is TNC'S guiding science principles and strategic framework[40] and an innovation for the organisation[16,19]. At its core, CbD 2.0 introduced approaches to address complex socio-ecological challenges. First, CbD 2.0 expanded the organisation's vision by emphasizing people as part of its conservation mission, reflecting the organisation's move from location-specific conservation projects to focusing on the biggest challenges facing nature and people. Second, CbD 2.0 sought to incorporate social science methods and evidence into TNC's policies and programs to explicitly address linkages between human well-being and nature. Finally, CbD 2.0 emphasized the process for developing conservation strategies that create systemic change (i.e., changing the economic, social, and other systems sustaining nature and people).

CbD 2.0 marked a significant shift in how TNC works, and there is demand for tools and methods to facilitate learning of CbD 2.0 concepts and practices. A survey on TNC's practices found only 33 percent of survey respondents stated they had "capacity with internal and external audiences on methods, tools and/or best practices" to assess the impacts conservation programs have on people. Further, CbD 2.0 provided the impetus for staff to adopt and integrate human well-being into their conservation programs, but TNC did not require staff to adopt CbD 2.0 and its emphasis on people. It instead relied on staff to recognize the needs and opportunities to create greater conservation impacts by incorporating people into their work. There is evidence of this recognized need. CbD 2.0 generated intense interest within TNC, as nearly 70 percent of staff attended a webinar introducing CbD 2.0 and its approach. Thus, the introduction of CbD 2.0, the growing recognition of the need to incorporate people into their strategies, and the relative novelty of incorporating human well-being with existing conservation work created an opportunity for practitioners to learn about and adopt new approaches to their conservation practice.

The tutorial addresses this organisational need, and was developed to help practitioners learn more about why and how human well-being can be incorporated into conservation strategies. Staff were not required to use or disseminate the tutorial. The tutorial consists of eight self-guided lessons that take approximately 10-20 minutes each. The lessons covered topics such as defining human well-being and introducing a human well-being framework, incorporating human well-being into results chains, developing human well-being hypotheses and objectives, developing and selecting socioeconomic indicators, socioeconomic monitoring and evaluation methods, and ethics when engaging people.

Our experiment takes place in the North America Region of TNC, which employs over 2,300 staff across 54 operating units (OUs) (approximately 58 percent of staff and 62 percent of OUs). The primary focus of OUs is to advance conservation goals within their respective geography and focal issues, which ultimately advance the organisation's mission. As a result, conservation activities are often focused within an OU's geography, and staff primarily collaborate and work within their OU, which is itself its own social system.

We randomly assigned 26 OUs to one of two conditions: 1) IBS targeting (hereinafter treatment) and 2) non-boundary spanner targeting (hereinafter control) groups. The experiment tested diffusion by sending an email inviting recipients to enrol in the online tutorial on human well-being and conservation, and encouraged original email recipients to forward the email to staff within their OU. In the treatment group, tutorial invitations were sent to all IBSs in the OU. For the control group, we selected a random subset of non-boundary spanners equal to the number of IBSs in the OU. Before randomization, we identified IBSs – and by extension the number of non-boundary spanners that would be contacted in the control group – by using labour hour data to identify clusters in bipartite networks and characterizing an individual's role as an IBS in terms of maintaining strong ties to projects outside as well as within one's cluster (see details in Methods). Email recipients received three emails: one invitation email and two follow up emails. Staff could only access the tutorial if they registered and attended a webinar, and a link to the registration was embedded within the email sent to the original email recipient. Thus, staff that were not originally invited could only access the link if they were forwarded an email from an original email recipient. As a result, our study examines decentralized diffusion because we do not instruct participants with whom they should communicate. Registrants were given over 50 different time slots over four days to attend the webinar to ensure scheduling constraints did not limit participation in the study.

The experiment allows us to investigate three questions covering nine hypotheses (Table 1) situated in the Diffusions of Innovation[16] process. We use data from administrative systems, staff surveys, and email platforms. We first investigate IBSs' receptivity to innovative information, their diffusion behaviour, and whether they affected OU-level interest in the innovation. We specifically examine their likelihood of opening emails (i.e., receptivity to information about an innovation), forwarding emails (i.e., diffusion of information about an innovation), enrolling in the tutorial at individual-level, and the collective actions at OU-level (i.e., interest in the innovation). Diffusion of innovations requires awareness about the innovation[16], and a precursor to awareness in our experiment is that email recipients must be receptive to new information. Our proxy variable for receptivity is a variable measuring the number of emails opened. IBSs are more receptive to new knowledge[26], and as a result we expect email opens to be greater than that of non-boundary spanners. Once staff are aware of an innovation, the innovation must be diffused within the OU[16]. IBSs can facilitate the flow of information between groups[17,20–23], and as an original email recipient we hypothesize that they will diffuse information about the innovation to a greater number of people than non-boundary spanners. Here, we proxy intra-OU email forwarding by using a variable indicating the number of times an email was opened. This variable leverages the fact that we can trace an email back to the original email recipient, which allows us to track whether the originating email was from an IBS. Finally, given greater diffusion behaviour within treated OUs, we expect greater enrolment in the tutorial indicating treated OUs have more staff at the Interest stage of adoption[16].

Our second set of hypotheses examines whether formal organisational roles moderate IBSs' diffusion behaviour. We test whether leadership roles (i.e., number of direct subordinates and organisational hierarchy) and formal boundary spanner status affect diffusion capacity. We hypothesize staff with more subordinates and whose formal role involves boundary spanning activities to be more likely to diffuse information about the innovation if they are also IBSs. In contrast, staff whose primary responsibilities involve management activities (i.e., strategy, supervisory activities) were less likely to diffuse information about the innovation because they may have limited time to engage in such activities.

Our final question examines whether diffusion of the tutorial changes staff attitudes and practices. CbD 2.0 aims to catalyse adoption of a number of sustainability practices, such as establishing new partnerships with outside organisations to incorporate new disciplinary perspectives[41]. We do not expect staff to significantly change all practices as a result of the tutorial because there is likely a time lag between the diffusion, adoption, and application of new knowledge[16]. However, staff in OUs who have heard about the tutorial may be more acutely aware of CbD 2.0's existence and begin adopting CbD 2.0 concepts in some of their work. Here, we use data on 18 attitudes and practices from a staff survey on CbD 2.0 concepts and practices from a subset of employees (from n=98 to n=420) to test whether being in the treated group significantly changes attitudes or practices, accounting for multiple hypothesis testing.

All hypotheses are tested using mixed effects models to account for the nesting of respondents in informal groups. Equations and model details are shown in the Methods section. Table 1 presents all hypotheses and main results, and detailed model results are in the Supplementary Information.

Results

We find IBSs play an important role in diffusing innovations for organisational learning. They were 2.8 times more likely to open the invitation email (β=1.0, $t(23)$=3.1, p < 0.01, H1 in Table 1) and four times more likely to forward the email compared to non-boundary spanners (β=1.4, $t(23)$=3.4, p < 0.01, H2 in Table 1). These results are robust, as 33 percent and 39 percent of the results, respectively, must be due to bias to invalidate the statistical inference[42]. Our results indicate that diffusion was not conditional on interest in an innovation, as IBSs were no more likely to enrol in the tutorial than non-boundary spanners (H3 in Table 1).

Our findings also indicate IBS behaviour increased OU-level receptivity to innovation and diffusion behaviour. We found a significant treatment effect on the number of people opening and diffusing the invitation email for OUs where IBSs were targeted. Targeting IBSs resulted in nearly twice the number of people opening emails (β=0.68, χ^2=4.1, p < 0.05, H4 in Table 1) and 3.5 times the number of people forwarding emails (β=1.3, χ^2=8.3, p < 0.01, H5 in Table 1) compared to OUs targeting non-boundary spanners.

IBSs' diffusion behaviour, however, can be affected by formal and informal organisational roles. We found a negative interaction effect between being an IBS and the number of direct subordinates (Figure 1a; β=-0.52, $t(137)$=-2.2, p < 0.01, H6 in Table 1). The significant conditional IBS effect (β=2.3, $t(22)$=3.4, p < 0.01) was offset when IBSs had 4 or more subordinates. Similarly, organisational hierarchy had a significant negative moderating effect on IBSs' diffusion behaviour (Figure 1b; β=-0.69, $t(137)$=-2.4, p < 0.05, H7 in Table 1). The significant conditional IBS effect on the probability of forwarding the invitation email (β=2.7, $t(22)$=3.4, p < 0.01) was offset when an IBS was at or above the fourth level of the organisational hierarchy. Individuals holding both informal and formal boundary spanner roles were no more likely to diffuse information than individuals only holding an IBS role (H8 in Table 1).

Finally, results indicate that diffusion of the tutorial did not result in any changes in practices targeted by CbD 2.0. But further analysis suggests staff changed attitudes on broad, transdisciplinary aspects of conservation work in early project stages (e.g., planning) that complement practices directly targeted by CbD 2.0. Out of 18 questions on attitudes and practices measured in a survey, staff in OUs where IBSs were targeted were more likely to agree that conservation applies in a greater number of contexts (β=0.22, $t(23)$=3.9, p<0.001, H9 in Table 1). This result remained statistically significant after applying the Bonferroni adjustment to account for the inflated Type I error rate. Further, using Frank et al.'s [42] robustness indices, 44 percent of the estimated effect would have to be due to bias to invalidate this statistical inference.

This result corresponds with qualitative interviews conducted with the same study population, and the qualitative data also provide support that the organisation was in the early stages of the Diffusions of Innovation process (i.e., awareness rather than implementation). The qualitative data come from 20 interviews conducted with 10 staff that were identified as IBSs, and 10 staff that were not IBSs. In those interviews, IBSs were more likely to express positive views about CbD 2.0 (70 percent vs. 20 percent), and they were also more interested in learning about CbD 2.0. IBSs also more commonly framed CbD 2.0 as a major change rather than an evolution of past practices in their statements (30 percent vs. 0 percent), and were more informed about CbD 2.0 (e.g., being able to articulate specific components of CbD 2.0 and its innovations) (40 percent vs. 10 percent). Interviews also indicated many viewed the organisation's conservation work can, and in some instances already does, incorporate people, although CbD 2.0 was new enough that a larger dialogue across the organisation had not yet occurred.

Discussion

Historically, TNC's approach involved conserving biodiversity through land acquisitions and conservation easements. The evolution of CbD provided a new focus on tackling sustainability challenges at the intersection of human well-being and nature conservation. As ENGOs like TNC work to safeguard the planet's life-support systems and address pressing sustainability challenges[43], they must continue to incorporate inter- and multidisciplinary approaches to their strategies[5,6]. This requires dynamism[44] and leveraging creative approaches to diffuse innovations for organisational learning, and ENGOs should pursue learning initiatives that fit their organisational culture and structure. Global ENGOs, such as TNC, increasingly have flatter organisational structures, and top-down approaches to diffuse innovations for organisational learning may be ineffective. Further, ENGO policies typically do not rely on purely technical solutions where knowledge is embedded in a technology (e.g., a chlorine tablet for clean water), and instead rely more on staff to adopt, adapt, and implement strategies (e.g., working with farmers to implement sustainable conservation agriculture practices). As a result, ENGOs may rely more on intraorganisational resources, such as IBSs, to disseminate knowledge to meet shifting demands and contexts.

We find IBSs can amplify diffusion about an innovation during the early stages of organisational learning, such as raising awareness and aligning attitudes about an innovation. Our findings suggest utilizing administrative data to leverage informal networks can help ENGOS diffuse innovations for organisational learning without relying on organisational mandates or costly training programs. Further, our analysis on staff attitudes and practices indicate diffusing innovations via IBSs led to more staff aligning their attitudes with the innovation. Changing attitudes is a preliminary step in behaviour change[45], and our results indicate sustainable, long-term changes that will eventually lead to changes in practices across the organisation. This effect is significant five months after the experiment – a time period long enough to suggest lasting changes in attitudes, indicating that targeting IBSs' did not create a temporary, immediate effect on staff attitudes and behaviours. From an organisational perspective, five months is a relatively short time period for changing organisational norms and practices in a complex social system.

Our study advances the social network and organisational learning literature in several ways. We use large administrative data to map informal social networks, making it possible to experimentally test IBSs' diffusion behaviour in a large sustainability-focused organisation. Further, most studies examining social network interventions do not investigate clusters, and instead focus on actor-specific characteristics, such as those with the highest in-degree, regardless of the network structure[46]. We instead explicitly analyse network structures, identify theoretically important actors, and test whether these actors can be leveraged for organisational learning. While past studies have found informal network actors are important for organisational learning[11,14,15,27,47,48], the focus of these studies has not been on IBSs, which take into account network structures and are unique from other actors often identified in informal networks[17,20–26,30]. Our findings support studies asserting boundary spanners may be strong change agents even though there may not be a strong association between being a boundary spanner and an early adopter of an innovation[26].

For ENGOs adapting to address sustainability challenges, our study demonstrates the possibility of using administrative data to generate sociograms for illuminating informal social network structures so as to facilitate understanding of the diffusion of innovations for organisational learning. In our study, IBSs identified via informal networks were significantly more likely to diffuse information about an innovation, which demonstrates how informal network attributes may especially be important for organisational learning. In global, geographically disperse ENGOs in particular, bipartite networks built using projects-level data may especially be appropriate for understanding dynamic informal networks, as staff can choose to participate in, and build, these emergent networks (i.e., co-generation). To facilitate organisational learning, our results suggest ENGOs can create venues (i.e., projects) to explicitly modify network structures[49], or link IBSs to external groups with new knowledge to leverage their unique network positions[24,50]. Like CbD 2.0, large ENGOs are increasingly interested in incorporating inter- and multidisciplinary approaches, and our results indicate mapping informal networks using administrative data opens new avenues for ENGOs to understand network structures to strategically allocate organisational resources. ENGOs are important stakeholders seeking to help advance sustainability goals, but they need to be dynamic and adaptable to articulate and design policies to address complex socio-ecological challenges. Our study indicates IBSs and administrative data can be an important resource for this process.

Methods

Sample

Our analytic sample consists of 821 staff from 26 OUs out of the 1,256 staff from 54 OUs. We excluded staff that left the organisation and were not full-time employees (seasonal or part-time) (n=63). We also excluded OUs with fewer than 10 staff because it was not possible to reliably identify clusters within these OUs (j=9, or n=64, where j represents OUs). Given the clustering analysis (described below in *Identifying IBSs*), we dropped three OUs because there were no clusters (n=39). This occurred in OUs where networks consisted of a long chain of people and projects, or when people were dropped because some individuals were the only ones connected to an event. Twelve OUs were dropped because they were partitioned for a separate study (n=262). Finally, of the OUs where we could identify clusters, we excluded OUs that had no IBSs (j=4, n=70). OUs that were not included in the study tended to have 21 less staff, 6 percent more conservation staff, 4 percent more executive staff, and 11 percent fewer science staff (see Supplementary Table 15).

Data

We primarily used administrative data and three primary data sources. Proprietary administrative data contain information on employee labour hours, staff attributes, formal organisational hierarchy, and participation in continued educational training. IBSs were identified using administrative staff labour hour data, which were pulled for July 4, 2014 to May 22, 2015. Labour hour data included data on project codes where staff charged their time. Primary data came from three sources. First, we used the Constant Contact platform to gather information on the number of total email opens and unique opens per recipient. Second, a registration and follow-up survey was created using Microsoft Sharepoint, which collected further information on staff referrals, perceptions, and conservation practices. A detailed timeline of the experiment and data collection events are shown in Supplementary Figure 4. Finally, we conducted a survey to collect longitudinal data on staff's conservation practices and beliefs, as well as questions on the CbD 2.0 practices. The baseline data collection was from May 12-June 26, 2015. The follow up survey was from May 5-June 9, 2016. The response rate for both survey rounds was 46 percent. We found people with higher job grades had a higher tendency to respond to the survey (β=0.34, $t(921)$=7.97, p < 0.001, Supplementary Table 13). Some OUs had a higher proportion of people responding to the survey (χ^2=53.56, df=25, p<0.001), although we found no differences in non-response between treatment and control OUs.

Identifying IBSs

Our experimental protocol requires us to identify IBSs before randomization. We identified IBSs using Field et al.'s [39] clustering technique for identifying clusters in bipartite networks for each of the 54 OUs using administrative labour hour data. The algorithm maximizes the odds ratio of an individual's participation in projects within their clusters relative to projects outside their clusters. Membership of people and projects in the same cluster increases the odds of the presence of network ties. The network data are defined by staff co-membership on projects within their OU. Connections between people and projects implies people are related to each other through common projects. To reflect tie strength, we weighed the connection between people and projects by the number of hours staff worked on a project, and applied inverse weights by the number of staff on a given project, where $tie\ strength = 1 + log(1 + \frac{work\ hours}{project\ size})$. This assumed work hours and project size increase and decrease, respectively, the likelihood of people interacting with each other. IBSs were identified based on clustering results. Individuals participating in at least three projects within and outside their clusters were identified as IBSs, as they are above the 75th percentile on the joint distribution of within and between cluster ties. In total, 25 percent of our sample was identified as IBSs. We also did not find observable characteristics (e.g., years at TNC, leadership positions) predict IBS status (see Supplementary Table 12).

Figure 2a illustrates the sociogram for an OU in our sample after clustering. The OU has 13 people participating in 24 projects, clustered into five groups. We identified five people as IBSs. The cluster in upper right corner of Figure 2a consists of one IBS, three non-boundary spanners, and six projects. The IBS with ID 7 has four within-group ties to in-group projects (IDs O, Q, S, and T), and three between-group ties to outside-group projects (IDs F, H, and W). In contrast, the non-boundary spanner with ID 10 has two within-group ties to in-group projects (IDs O and T). Through an individual's location in the sociogram, we can see the staff with ID 7 has a structural advantage compared to the staff with ID 10 to engage in boundary-spanning activities within and across clusters to diffuse innovations.

Experiment protocol

Our experimental protocol followed a five-step process (see Supplementary Figure 8) and employed a randomized block design. We first identified IBSs using administrative data (described above). We then calculated the proportion of people in the OU identified as IBSs. Given that an individual's boundary spanning behaviour could be influenced by the proportion of IBSs in an OU, we introduced a blocking variable (i.e. the proportion of people in each OU that are IBSs) into the experimental design to decrease the within group variability and increase precision and statistical power (see Supplementary Figure 4). We created two blocks. The first block included OUs where the proportion of people that are IBSs is below the overall median, and the second block is for OUs above the median. Sociograms in Figure 2a and 2b are two OUs that have an equivalent proportion of staff in the OU that are IBSs (i.e., 40 percent above the median proportion, and hence are included in the second block).

Twenty-six OUs were assigned to 1) IBS targeting (treatment) and 2) non-boundary spanner targeting (control) groups. The sociogram presented in Figure 2a and 2b illustrates the randomization and experimental protocol. Figure 2a presents a sociogram for the treatment group, and Figure 2b presents a sociogram for the control group. For our experiment, we sent an email invitation to IBSs in the treatment group, and email invitations to an equivalent number of non-boundary spanners in the control group (e.g., nodes with a orange circle in Figure 2a and 2b were targeted for the experiment). In other words, for the control group we selected a random subset of non-boundary spanners equal to the number of IBSs in the OU. In the case of the OU represented in Figure 2b, there are six IBSs, which meant we randomly selected six non-boundary spanners to receive the email (represented by nodes with orange circles).

The tutorial invitation (see Supplementary Figure 1) encouraged staff to participate in pilot testing an online tutorial on human well-being and conservation. Initial email recipients received three emails: one invitation email and two follow up emails. The email message encouraged staff to register to learn more about the tutorial via a 30-minute webinar that provided a brief description and access to the tutorial. All email recipients were encouraged to forward the email to relevant staff within their OUs. Staff could only access the tutorial if they registered and attended the webinar, and could only register and access the tutorial if they received the email invitation from an original email recipient.

Dependent variables

We tested our hypotheses using five dependent variables, which came from the Constant Contact system, TNC's internal tutorial registration system, and online surveys. The Constant Contact system tracked emails through images and links embedded in emails. To maximize image and link tracking, all invitation emails prominently encouraged staff to load images in the email, and we also included details about the tutorial within the image (see Supplementary Figure 1).

We first created a binary variable indicating whether the recipient opened the tutorial invitation email. This variable represents receptivity to new information. We employ a binary proxy variable representing whether the email recipient forwarded the invitation to staff within their OUs, which captures diffusion behaviour. The variable was assigned a value of one if the recipient opened the email at least three times. We believe this is a plausible assumption given that email recipients are unlikely to open an email more than twice, even if by accident. Our third outcome variable comes from the registration system, and is a binary variable assigned a value of one if a staff registered for the human well-being tutorial and zero otherwise. This variable represents interest in the innovation by the email recipient. Furthermore, we developed two OU-level variables capturing whether targeting all IBSs had an overall effect on measures within the OU. Our first variable measured the total number of opens within an OU. The second variable is a binary variable where we measured the total number of people in an OU who forwarded at least one email within an OU. To assess changes in practice, we examined 18 attitudes and practices in the staff survey, each using a 4-point Likert-scale with responses ranging from strongly disagree to strongly agree. Attitudes and practices are listed in Supplementary Table 11.

Empirical strategy

We estimated generalized linear mixed-effects models utilizing an adaptive Gaussian quadrature for binary outcomes. Models were fitted with predictors at the staff-level, OU-level, and with cross-level interactions. Because we designed the experiment at OU-level, which exclusively targeted either IBSs or non-boundary spanners for information diffusion in a given OU, we estimated the IBS effect via an OU-level treatment status indicator, accounting for the dependence of individual's behaviour within each OU. As a result, we interpret the treatment status variable as the IBS effect for all generalized linear mixed effects models. For OU-level aggregated count outcomes, we estimated generalized linear models because outcomes were continuous. For continuous outcome variables, we used a mixed effect general linear model to test the OU treatment effect on individual changes in practice [51].

We used HLM7 to estimate generalized linear mixed effects models. *H1-H3* tested OU-level treatment effects of targeting IBSs on opening emails, forwarding emails, and enrolling in the tutorial (professional development), respectively. We use the outcome, forwarding emails, as an example below for the model specification. The other two outcomes follow the same model specification. The model estimated the following for individual i in OU j such that:

Link function:

$$\Pr(\textit{forwarding emails}_{ij}=1|\beta_j) = \phi_{ij}$$

$$\log[\phi_{ij}/(1 - \phi_{ij})] = \eta_{ij}$$

Mixed model:

$$\eta_{ij} = \gamma_{00}$$
$$+ \gamma_{01}*\textit{treatment}_j$$
$$+ \gamma_{02}*\textit{block}_j$$
$$+ u_{0j}$$

where η_{ij} is the transformed individual-level dependent variable of *forwarding emails*$_{ij}$. The coefficient of interest is γ_{01}, which represents the OU-level treatment effect of targeting IBSs for information diffusion.

For *H6-H8*, we tested the cross-level interaction of an individual's leadership role and IBS status of forwarding emails for individual *i* in OU *j*. We use the number of direct subordinates as an example for the model specification. All other leadership roles (i.e., organisational hierarchy [continuous count variable] and formal boundary spanner designation [binary variable]) have the same model specification.

Link function:

$$\Pr(\textit{forwarding emails}_{ij}=1|\beta_j) = \phi_{ij}$$

$$\log[\phi_{ij}/(1 - \phi_{ij})] = \eta_{ij}$$

Mixed model:

$$\eta_{ij} = \gamma_{00}$$
$$+ \gamma_{01}*\textit{treatment}_j$$
$$+ \gamma_{02}*\textit{block}_j$$
$$+ \gamma_{10}*\textit{the number of direct subordinates}_{ij}$$
$$+ \gamma_{11}*\textit{treatment}_j*\textit{the number of direct subordinates}_{ij}$$
$$+ u_{0j}$$

where η_{ij} is the transformed dependent variable of *forwarding emails*$_{ij}$. The coefficient γ_{11} is the moderating effect of the number of direct subordinates, on the treatment effect of targeting IBSs for information diffusion on individual's likelihood of forwarding emails. γ_{01} and γ_{10}. γ_{01} represents the OU-level treatment effect of targeting IBSs for information diffusion. γ_{10}, meanwhile, is the individual-level effect of the number of direct subordinates on the likelihood of forwarding emails.

For *H4* and *H5* we estimated a generalized linear model. The dependent variable is the aggregated measure at the OU-level, *j*. We use the outcome for the number of people who forwarded the email in OU j to illustrate our model specification. Other count outcomes follow the same model specification. The model takes the form:

Link function:

$$\log(\textit{the number of people forwarding emails in } OU_j) = \eta_j$$

Model:

$$\eta_j = \gamma_0$$
$$+ \gamma_1 * treatment_j$$
$$+ \gamma_2 * block_j$$
$$+ u_j$$

where η_j is the transformed dependent count variable. γ_1 represents the treatment effect of targeting IBSs for information diffusion on the total number of people forwarding emails at OU level.

For H9, we estimated the OU-level treatment effect of targeting IBSs on individual-level changes in practice for 18 attitudes and practices. We applied a Bonferroni adjustment to account for the inflated Type I error rate, and also used Frank et al.'s [42] robustness indices. Below is an example for the model specification.

Mixed model:

$$\textit{CbD 2.0 approach increased the contexts we can work}_{ij} = \gamma_0$$
$$+ \gamma_1 * treatment_j$$
$$+ \gamma_2 * block_j$$
$$+ u_j$$
$$+ r_{ij}$$

where the dependent variable is a change score on individual's beliefs on the number of contexts they can work as a result of applying CbD 2.0 approaches. The coefficient of interest is γ_1, and represents the OU-level treatment effect of targeting IBSs for information diffusion on individual's change in their beliefs.

Randomization

Randomization checks revealed original email recipients in the treatment and control groups were largely similar on observable characteristics (see Supplementary Table 14). Organisational tenure, salaries, professional development training, membership in communities of practice and other variables were largely the same. There were, however, two significant differences between the original email recipients in the treatment and control groups. Original email recipients in the treatment groups consisted of more staff members in the Executive job family (7.1 percent) and had more direct reports, although the difference is negligible at fewer than one staff (0.51). These observable differences are only present in the second randomization block (i.e., the number of IBSs above the overall median). Staff in the Executive job family are typically responsible for administrative tasks with some managerial responsibilities, and hold positions such as Program Director and Chief of Staff. Staff in these positions may be more likely to engage in formal boundary spanning activity, but our study explores informal boundary spanning activity. We also explored variation in both formal hierarchy and network position and found diffusion behaviour did not significantly vary by formal boundary spanner status. To hold constant the difference on the number of direct reports, we included this variable in the model when estimating the treatment effect (see Supplementary Table 8-9).

Internal validity and robustness checks

There are several threats to internal validity, but we fail to find compelling evidence that they are concerning for our overall results. Spillover of email invitations to other OUs is perhaps the largest threat to internal validity. Invitation emails explicitly asked for emails to only be diffused within OUs, but email recipients may have overlooked this request. We find no evidence of spillover from communications. For instance, individuals that registered for the webinar only reported receiving emails from staff within their OU. In addition, original email recipients may have known the email sender, making it more likely to open and send the email to staff. The email sender, however, knew two people of the original 178 email recipients, making it unlikely this is a threat to internal validity.

Our study relies on the assumption that bipartite network data provide a good approximation of informal social networks. While formal social networks based on organisational hierarchy are relatively easy to identify, informal networks typically rely on survey data. We believe our bipartite network data are largely representative of informal networks. Frank et al. [52] demonstrated ties in affiliation networks could predict ties in self-reported friendship network, providing support for this assumption. A subset analysis for two groups using informal network data collected via a sociometric approach with over 70 percent response rates from our study population revealed odds ratios above 50 for administrative data to predict sociometric ties. Finally, labour hours and project code data represent how staff at TNC operate and interact, adding further confidence that bipartite network data represent informal networks. TNC's funding structure dictates staff account for every hour of their day to project codes. As a result, we believe the administrative labour hour data are representative of the regular informal interactions that take place in the work place.

Limitations

Our results and investigation indicate several areas for further study. First, our study employed a proxy variable for forwarding behaviour, and future work should focus on gathering direct measures of forwarding behaviour. However, we recognize this may be challenging due to privacy concerns. In addition, while our results demonstrate IBSs diffuse innovations more than non-boundary spanners, further work should explore what drives these behaviours. IBSs may be more receptive to new information because of their diverse project portfolio and work environments. They also have a potentially larger target audience to diffuse innovations compared to non-boundary spanners, and they are believed to play an active role in diffusing innovation [20,21,29]. It is also possible that IBSs are interested in the innovation and, as a consequence, engaged in professional development activities that promote innovation adoption, although our study did not find that IBSs were more likely to enrol in the tutorial. IBSs may also have distinct intrinsic characteristics that make them behave differently from non-boundary spanners. For instance, IBSs may be more extroverted, thus driving their overall propensity to engage in diffusion behaviours. They may also have motivations that may or may not be parallel to advancing the organisational mission[32,47,53]. Finally, future studies should allow a longer time lag between an experiment and measurement of staff attitudes and behaviours, or practices.

Data availability statement

Data may be available upon request subject to permission from The Nature Conservancy. These data are under license for the current study from The Nature Conservancy and restrictions apply to the availability of these data.

Ethics statement

The project was reviewed by the Human Subjects Research Reviewer at The Nature Conservancy, and the primary survey data and protocol to collect was approved by Michigan State University's Institutional Review Board. Because there was minimal risk of harm to participants from being sent an email it was not necessary to submit the project for institution-wide ethics review.

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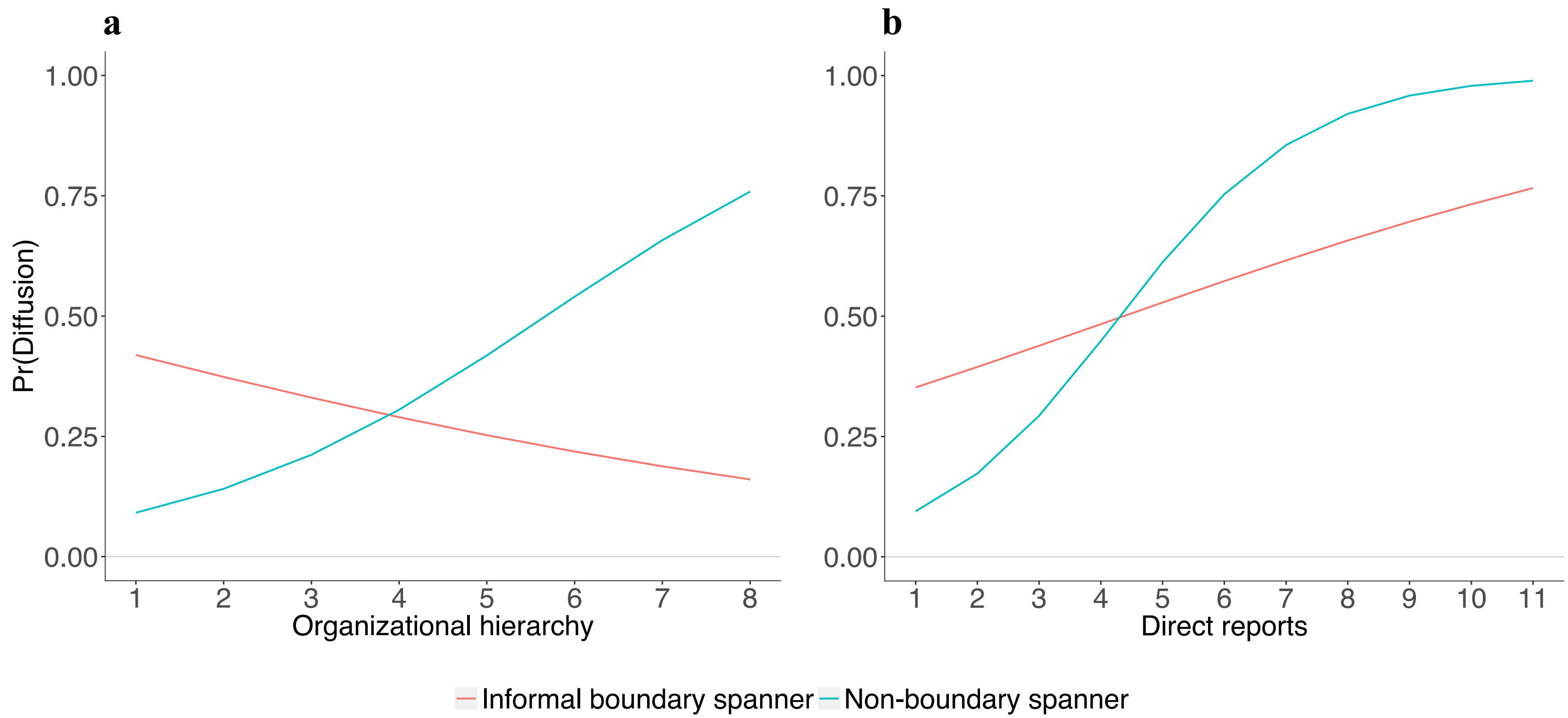

Figure 1: Adjusted predictions of diffusion by number of direct reports and organizational hierarchy. **a.** displays the adjusted predictions of diffusion by number of direct reports. Having an organizational hierarchy above the fourth level offset the IBS effect on the probability of forwarding the invitation email. **b.** displays the adjusted predictions of diffusion by organizational hierarchy. The significant IBS effect was offset when staff had four or more subordinates. Shaded areas represent 95% confidence intervals. Pink lines and shaded areas are for IBSs and blue lines and shaded areas are for non-boundary spanners.

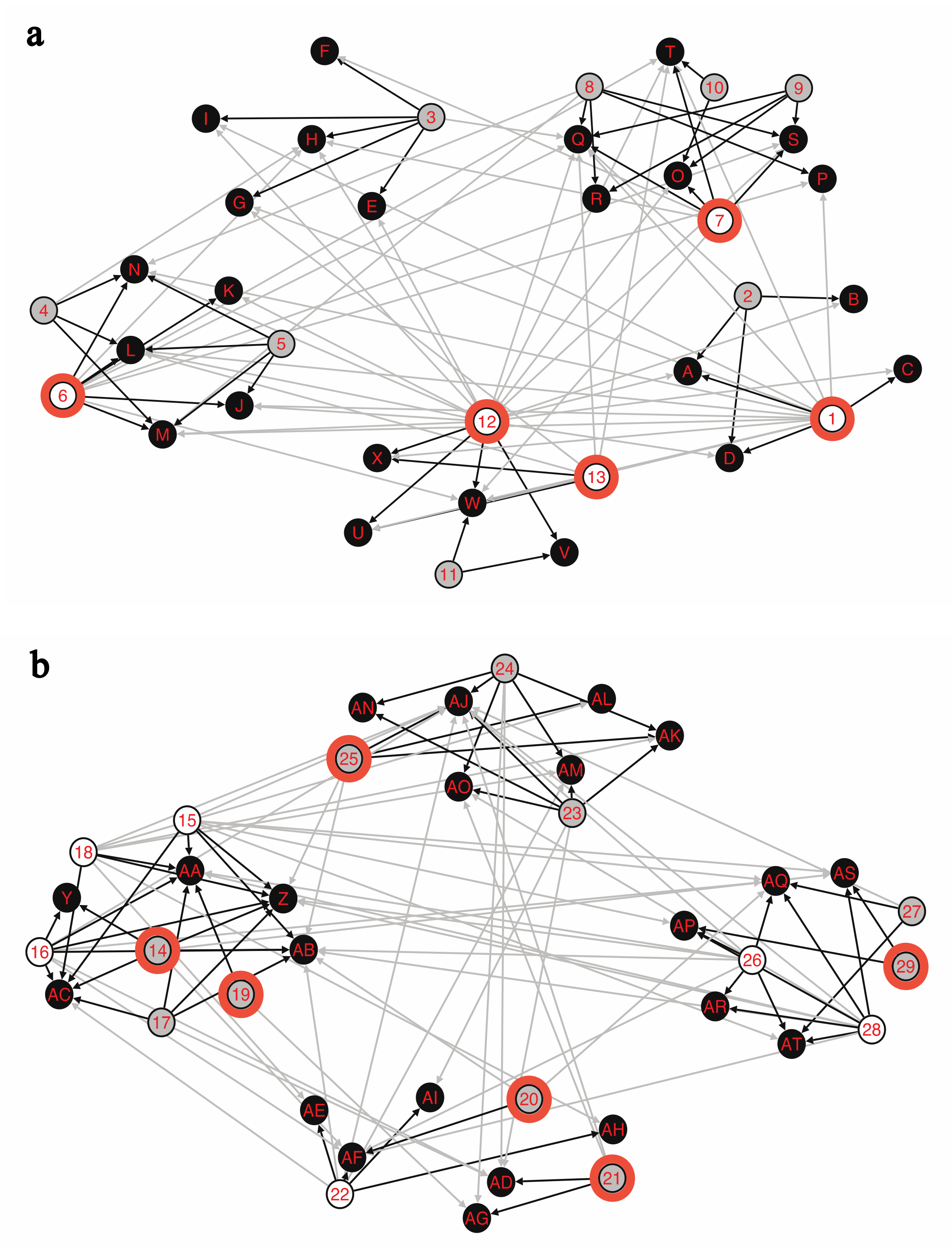

Figure 2: Sociograms for treatment and control operating units within the North America Region of The Nature Conservancy. **a.** presents a sociogram for an OU in the treatment group, and **b.** presents a sociogram for an OU in the control group. IBSs are represented by white nodes, non-boundary spanners are represented by grey nodes, and projects are represented by black nodes. Nodes with orange circles are people targeted by the experiment. Black lines represent ties from people to projects in the same cluster, and grey lines represent ties from people to projects in different clusters.

Correspondence and requests for materials should be addressed to YJM.

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Author contributions
YJM, YL, SMWR, and KAF designed the research; YJM, YL, SMWR, KB, and JRBF performed research; YJM, YL, and KAF analyzed data; and YJM, YL, SMWR, KAF, KB, JRBF, and JM wrote the paper.