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Innovation diffusion within large environmental NGOs through informal network agents

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The Sustainable Development Goals present opportunities for environmental non-governmental organizations (ENGOs) to address new challenges. Such innovation requires dynamism and adaptability that large ENGOs may lack, and flatter organizational 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—individuals who cross internal organizational boundaries (for example, 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 organizational positions (for example, formal organizational 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 informal boundary spanners can drive organization-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 organizations (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 organizational learning, adoption, and adaptation[3,4,7,8]. This is especially critical for large, decentralized organizations that may lack sufficient direct authority or staff oversight to guarantee uptake of new resources and approaches. For instance, large conservation organizations, such as the World Wildlife Fund and The Nature Conservancy (TNC), operate in dozens of countries in diverse contexts, making top-down change challenging. Organizational leaders may appeal to formal authority[9] to diffuse innovations and promote organizational learning, but these approaches assume innovations can spread and be integrated through rigid, formal, and hierarchical organizational 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 organizational 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, informal boundary spanners (IBSs) in particular are uniquely positioned within informal social networks to diffuse innovations and promote organizational learning, especially in the early stages of intraorganizational diffusion of innovations[16–20]. IBSs are self-selected individuals who are strongly tied to staff within and outside their day-to-day (that is, informal) work environments (that is, clusters), and are distinct from formal boundary spanners who hold formal organizational roles that include boundary-spanning activities[20–22]. Research has found IBSs can facilitate the flow of information between people or groups who may have minimal communication with each other[17,20,21,23,24]; are uniquely situated to develop insights into organizational structures and cultures[21]; often straddle multiple organizational units and may demonstrate unique skills to handle complicated tasks in different contexts[20,21,25,26]; and are more receptive to new knowledge and more responsive to change[27]. IBSs differ from bridges (actors tying two loosely connected clusters) and other actors within informal networks[23], as they balance the advantages of bridging (exchanging information between groups) and bonding (consolidating the collaboration within their primary group) by distributing their social capital equally to projects within and outside their cluster[28]. They also provide less redundant information[11], and are more efficient in spreading information inside and outside their cluster[29] 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 (those spanning between two clusters) or formal boundary spanners (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 organizational 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 (actors whose primary responsibilities include boundary-spanning activities)[20,29,33]. Studies on large organizations

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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[27]. Studies testing aspects of diffusions of innovations using social network experiments have been in non-organizational 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 TNC, one of the world's largest non-profit conservation organizations[36], to construct a bipartite network[37–39] and experimentally test the role of IBSs in diffusion of innovations for organizational learning. Thus, our approach allows us to identify IBSs in a large ENGO, randomly assign them to experimental conditions, and estimate their role in diffusion of innovations for organizational 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 organizational learning compared to non-boundary spanners. CbD 2.0 is the guiding science principles and strategic framework[40] of TNC and an innovation for the organization[16,19]. At its core, CbD 2.0 introduced approaches to address complex socio-ecological challenges. First, CbD 2.0 expanded the organization's vision by emphasizing people as part of its conservation mission, reflecting the organization'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 programmes 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 (that is, 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 that only 33 per cent of survey respondents stated they had "capacity with internal and external audiences on methods, tools and/or best practices" to assess the impacts conservation programmes have on people. Further, CbD 2.0 provided the impetus for staff to adopt and integrate human well-being into their conservation programmes, 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 per cent 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 organizational 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 (approximately 58 per cent of staff and 62 per cent of operating units). The primary focus of operating units (OUs) is to advance conservation goals within their respective geography and focal issues, which ultimately advance the organization's mission. As a result, conservation activities are often focused within an operating unit's geography, and staff primarily collaborate and work within their operating unit, which is itself its own social system.

We randomly assigned 26 operating units to one of two conditions: (1) IBS targeting (hereinafter treatment) and (2) non-boundary spanner targeting (hereinafter control) groups (see operating unit examples for each condition in Fig. 1). 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 operating unit. In the treatment group, tutorial invitations were sent to all IBSs in the operating unit. For the control group, we selected a random subset of non-boundary spanners equal to the number of IBSs in the operating unit. 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 operating-unit-level interest in the innovation. We specifically examine their likelihood of opening emails (receptivity to information about an innovation), forwarding emails (diffusion of information about an innovation), enrolling in the tutorial at an individual level, and the collective actions at operating-unit level (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[27], 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 operating unit[16]. IBSs can facilitate the flow of information between groups[17,20,21,23,24], 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-operating-unit 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 operating units, we expect greater enrolment in the tutorial indicating treated operating units have more staff at the interest stage of adoption[16].

Our second set of hypotheses examines whether formal organizational roles moderate IBSs' diffusion behaviour. We test whether leadership roles (number of direct subordinates and organizational hierarchy) and formal-boundary-spanner status affect

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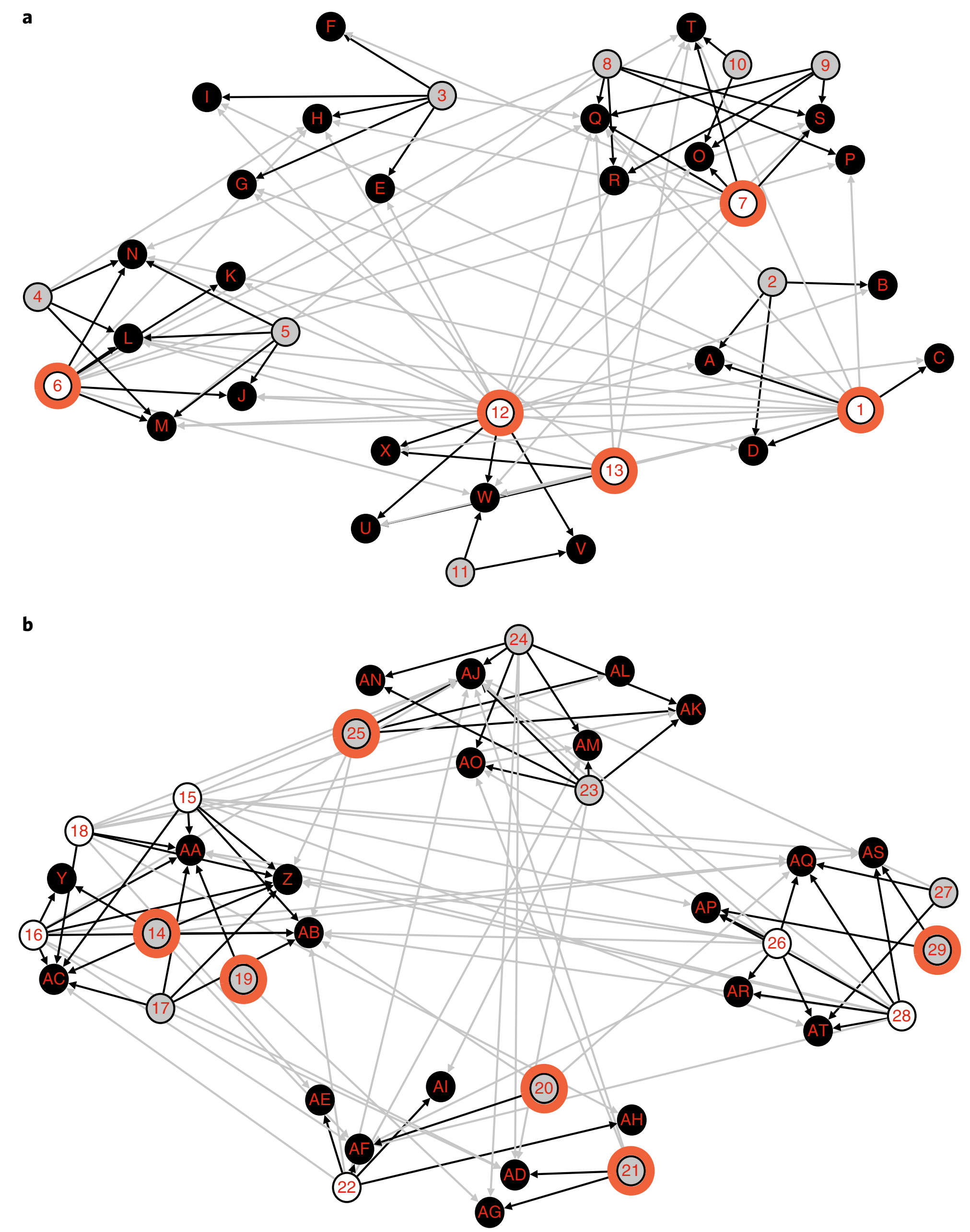

Fig. 1 | Sociograms for treatment and control operating units within the North America region of TNC. a, A sociogram for an operating unit in the treatment group. **b**, A sociogram for an operating unit in the control group. IBSs are represented by white nodes, non-boundary spanners are represented 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.

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. By contrast, staff whose primary responsibilities involve management activities (that is, 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 organizations 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 operating units who have heard about the tutorial may be more acutely aware of CbD 2.0 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.

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Table 1 | Research questions, hypotheses and results

Hypothesis	Model	Coefficient
Are IBSs more receptive to innovations, and do they diffuse innovation compared to non-boundary spanners?		
(H1) Boundary spanners are more likely to read emails.	A	1.0** (0.33)
(H2) Boundary spanners are more likely to diffuse information.	A	1.4** (0.41)
(H3) Boundary spanners are more likely to enroll in the human well-being and conservation tutorial.	A	0.18 (0.59)
(H4) More staff read invitation emails in operating units that target informal boundary spanners.	B	0.68* (0.34)
(H5) More people diffuse innovation in operating units that target informal boundary spanners.	B	1.3** (0.44)
Do other organizational roles moderate the effect of IBS status on diffusing innovation?		
(H6) Boundary spanners' diffusion activity will be positively moderated by their supervisory position.	A	−0.52** (0.20)
(H7) Organizational hierarchy has a negative moderating effect on boundary spanners' likelihood of diffusing innovation.	A	−0.69** (0.28)
(H8) IBSs' diffusion behaviour will be positively moderated by their formal boundary spanner role.	A	−1.1 (0.80)
Did diffusion of the tutorial lead to staff changing attitudes and adopting CbD 2.0 practices?		
(H9) Staff in operating units where IBSs were targeted changed attitudes or adopted new practices.	C	0.22*** (0.06)

A, B and C in the column 'Model' refer to multilevel logistic regression, negative binomial regression and multilevel linear regression, respectively. Dependent variables for the models are as follows: (H1) one if opened email; (H2, H6–H8) one if email opened more than three times; (H3) one if registered for tutorial; (H4) total email opens at the operating-unit level; (H5) total number of people at the operating-unit level; (H9) four-point Likert scale. Coefficients display the IBS effect for H1–H5 and H9, and the interaction effect of being an IBS and a staff's organizational role for H6–H8. For H9 we tested 18 attitudes and practices, one of which was statistically significant after conducting a Bonferonni adjustment and using robustness indices described previously[42]. We present the results for the question asking, "To what extent do you agree that applying the CbD 2.0 approach has increased the number of contexts in which we can work?" Full model results are presented in Supplementary Tables 2,4–11. Results for all attitudes and practices tested in H9 are shown in Supplementary Table 11. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

Results

We find IBSs play an important role in diffusing innovations for organizational learning. They were 2.8 times more likely to open the invitation email ($\beta = 1.0$, $t(23) = 3.1$, $p < 0.01$, H1 in Table 1) and four times more likely to forward the email compared to non-boundary spanners ($\beta = 1.4$, $t(23) = 3.4$, $p < 0.01$, H2 in Table 1). These results are robust, as 33 per cent and 39 per cent 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 operating-unit-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 operating units where IBSs were targeted. Targeting IBSs resulted in nearly twice the number of people opening emails ($\beta = 0.68$, $\chi^2 = 4.1$, $p < 0.05$, H4 in Table 1) and 3.5 times the number of people forwarding emails ($\beta = 1.3$, $\chi^2 = 8.3$, $p < 0.01$, H5 in Table 1) compared with operating units targeting non-boundary spanners.

IBSs' diffusion behaviour, however, can be affected by formal and informal organizational roles. We found a negative interaction effect between being an IBS and the number of direct subordinates (Fig. 2a; $\beta = -0.52$, $t(137) = -2.2$, $p < 0.01$, H6 in Table 1). The significant conditional IBS effect ($\beta = 2.3$, $t(22) = 3.4$, $p < 0.01$) was offset when IBSs had four or more subordinates. Similarly, organizational hierarchy had a significant negative moderating effect on IBSs' diffusion behaviour (Fig. 2b; $\beta = -0.69$, $t(137) = -2.4$, $p < 0.05$, H7 in Table 1). The significant conditional IBS effect on the probability of forwarding the invitation email ($\beta = 2.7$, $t(22) = 3.4$, $p < 0.01$) was offset when an IBS was at or above the fourth level of the organizational 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).

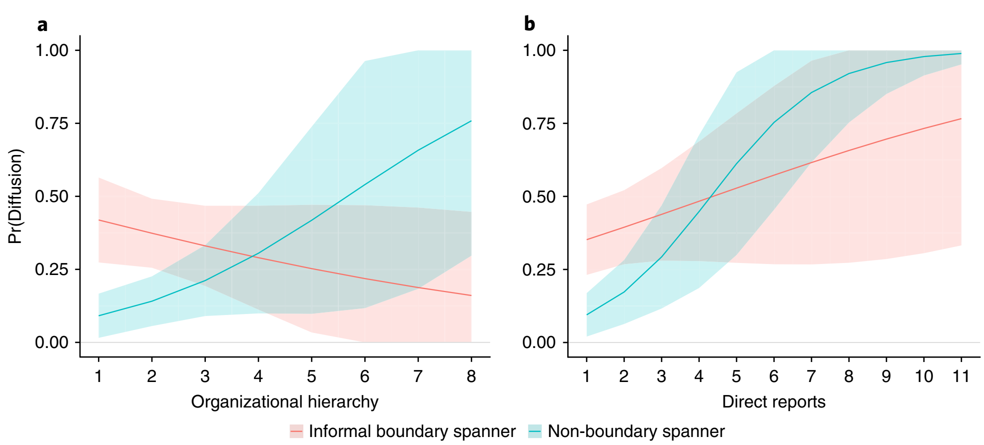

Fig. 2 | Adjusted predictions of diffusion by number of direct reports and organizational hierarchy. a, The adjusted predictions of diffusion by number of direct reports. Having an organizational hierarchy above the fourth level offset the IBS effect on the probability of forwarding the invitation email. **b**, 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.

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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 (for example, planning) that complement practices directly targeted by CbD 2.0. Out of 18 questions on attitudes and practices measured in a survey, staff in operating units where IBSs were targeted were more likely to agree that conservation applies in a greater number of contexts ($\beta = 0.22$, $t(23) = 3.9$, $p < 0.001$, 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 robustness indices reported previously[42], 44 per cent 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 organization was in the early stages of the diffusions of innovation process (that is, awareness rather than implementation). The qualitative data come from 20 interviews conducted with 10 staff who were identified as IBSs, and 10 staff who were not IBSs. In those interviews, IBSs were more likely to express positive views about CbD 2.0 (70 per cent versus 20 per cent), 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 per cent versus 0 per cent), and were more informed about CbD 2.0 (for example, being able to articulate specific components of CbD 2.0 and its innovations) (40 per cent versus 10 per cent).

Discussion

Historically, the approach of TNC 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 organizational learning, and ENGOs should pursue learning initiatives that fit their organizational culture and structure. Global ENGOs, such as TNC, increasingly have flatter organizational structures, and top-down approaches to diffuse innovations for organizational learning may be ineffective. Further, ENGO policies typically do not rely on purely technical solutions where knowledge is embedded in a technology (for example, a chlorine tablet for clean water), and instead rely more on staff to adopt, adapt and implement strategies (for example, working with farmers to implement sustainable conservation agriculture practices). As a result, ENGOs may rely more on intraorganizational 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 organizational 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 organizational learning without relying on organizational mandates or costly training programmes. 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 organization. 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 organizational perspective, five months is a relatively short time period for changing organizational norms and practices in a complex social system.

Our study advances the social network and organizational 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 organization. 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 organizational learning. Although past studies have found informal network actors are important for organizational learning[11,14,15,28,47,48], 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[17,20,21,23–27,30]. 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[27].

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 organizational 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 organizational 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 (co-generation). To facilitate organizational learning, our results suggest ENGOs can create venues (projects) to explicitly modify network structures[49], or link IBSs to external groups with new knowledge to leverage their unique network positions[25,50]. 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 organizational 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 operating units out of the 1,256 staff from 54 operating units. We excluded staff who left the organization and were not full-time employees (seasonal or part-time) ($n = 63$). We also excluded operating units with fewer than 10 staff because it was not possible to reliably identify clusters within these operating units ($j = 9$, or $n = 64$, where j represents operating units). Given the clustering analysis (described below in 'Identifying IBSs'), we dropped three operating units because there were no clusters ($n = 39$). This occurred in operating units 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 operating units were dropped because they were partitioned for a separate study ($n = 262$). Finally, of the operating units where we could identify clusters, we excluded operating units that had no IBSs ($j = 4$, $n = 70$). Operating units that were not included in the study tended to have 21 fewer staff, 6 per cent more conservation staff, 4 per cent more executive staff, and 11 per cent 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 organizational hierarchy, and participation in continued educational training. IBSs were identified using administrative staff labour hour data, which were pulled for 4 July 2014 to 22 May 2015. Labour hour data included data on project codes where staff charged their time. Primary data came from three

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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 Fig. 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 12 May–26 June 2015. The follow-up survey was from 5 May–9 June 2016. The response rate for both survey rounds was 46 per cent. We found people with higher job grades had a higher tendency to respond to the survey ($\beta = 0.34$, $t(921) = 7.97$, $p < 0.001$, Supplementary Table 13). Some operating units had a higher proportion of people responding to the survey ($\chi^2 = 53.56$, d.f. = 25, $p < 0.001$), although we found no differences in non-response between treatment and control operating units.

Identifying IBSs. Our experimental protocol requires us to identify IBSs before randomization. We identified IBSs using a clustering technique reported previously[39] for identifying clusters in bipartite networks for each of the 54 operating units 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 operating unit. Connections between people and projects imply 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 $= 1 + \log\left(1 + \frac{\text{work hours}}{\text{project size}}\right)$. 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 per cent of our sample were identified as IBSs. We also did not find that observable characteristics (for example, years at TNC, leadership positions) predict IBS status (see Supplementary Table 12).

Figure 1a illustrates the sociogram for an operating unit in our sample after clustering. The operating unit has 13 people participating in 24 projects, clustered into 5 groups. We identified five people as IBSs. The cluster in upper right corner of Fig. 1a 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.

Experimental protocol. Our experimental protocol followed a five-step process (see Supplementary Fig. 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 operating unit identified as IBSs. Given that an individual's boundary-spanning behaviour could be influenced by the proportion of IBSs in an operating unit, we introduced a blocking variable (that is, the proportion of people in each operating unit who are IBSs) into the experimental design to decrease the within-group variability and increase precision and statistical power (see Supplementary Fig. 4). We created two blocks. The first block included operating units where the proportion of people who are IBSs is below the overall median, and the second block is for operating units above the median. Sociograms in Fig. 1a,b are two operating units that have an equivalent proportion of staff who are IBSs (that is, 40 per cent above the median proportion, and hence are included in the second block).

Twenty-six operating units were assigned to (1) IBS targeting (treatment) and (2) non-boundary spanner targeting (control) groups. The sociograms presented in panels a and b of Fig. 1 illustrate the randomization and experimental protocol. Fig. 1a presents a sociogram for the treatment group, and Fig. 1b 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 (for example, nodes with a orange circle in Fig. 1a,b 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 operating unit. In the case of the operating unit represented in Fig. 1b, 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 Fig. 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 operating units. 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 Fig. 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 operating units, 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 operating-unit-level variables capturing whether targeting all IBSs had an overall effect on measures within the operating unit. Our first variable measured the total number of opens within an operating unit. The second variable is a binary variable where we measured the total number of people in an operating unit who forwarded at least one email within an operating unit. 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, operating-unit level and with cross-level interactions. Because we designed the experiment at operating-unit level, which exclusively targeted either IBSs or non-boundary spanners for information diffusion in a given operating unit, we estimated the IBS effect via an operating-unit-level treatment status indicator, accounting for the dependence of individuals' behaviour within each operating unit. As a result, we interpret the treatment status variable as the IBS effect for all generalized linear mixed effects models. For operating-unit-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 operating-unit treatment effect on individual changes in practice[51].

We used HLM7 to estimate generalized linear mixed effects models. H1–H3 tested operating-unit-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 an individual i in operating unit j such that:

Link function:

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

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

Mixed model:

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

where η_{ij} is the transformed individual-level dependent variable of 'forwarding emails$_{ij}$'. The coefficient of interest is γ_{01}, which represents the operating-unit-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 operating unit j. We use the number of direct subordinates as an example for the model specification. All other leadership roles (that is, organizational hierarchy [continuous count variable] and formal boundary spanner designation [binary variable]) have the same model specification.

Link function:

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

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

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Mixed model:

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

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 an individual's likelihood of forwarding emails. γ_{01} represents the operating-unit-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 operating-unit level, j. We use the outcome for the number of people who forwarded the email in operating unit j to illustrate our model specification. Other count outcomes follow the same model specification. The model takes the form:

Link function:

$$\log(\text{the number of people forwarding emails in OU}_j) = \eta_j$$

Model:

$$\eta_j = \gamma_0 + \gamma_1\text{treatment}_j + \gamma_2\text{block}_j + u_j$$

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 operating-unit level.

For H9, we estimated the operating-unit-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 robustness indices reported previously[42]. Below is an example for the model specification.

Mixed model:

$$\text{CbD 2.0 approach increased the contexts we can work}_{ij} = \gamma_0 + \gamma_1\text{treatment}_j + \gamma_2\text{block}_j + u_j + r_{ij}$$

where the dependent variable is a change score on an 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 operating-unit-level treatment effect of targeting IBSs for information diffusion on an 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). Organizational 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 per cent) 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 (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 Tables 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 operating units is perhaps the largest threat to internal validity. Invitation emails explicitly asked for emails to only be diffused within operating units, 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 operating unit. 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 2 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 organizational 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, although 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[20–22]. 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 organizational 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.

Ethics statement. The project was reviewed by the Human Subjects Research Reviewer at TNC, 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.

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

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Author contributions

Y.J.M., Y.L., S.M.W.R. and K.A.F. designed the research; Y.J.M., Y.L., S.M.W.R., K.B. and J.R.B.F. performed the research; Y.J.M., Y.L. and K.A.F. analysed data; and Y.J.M., Y.L., S.M.W.R., K.A.F., K.B., J.R.B.F. and J.M. wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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